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LCIA framework and modelling guidance [TF 1 Crosscutting issues]

Verones, Francesca ; Henderson, Andrew D.; Laurent, Alexis; Ridoutt, Brad; Ugaya, Cassia; Hellweg, Stefanie

Published in:
Global guidance for life cycle impact assessment indicators

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Verones, F., Henderson, A. D., Laurent, A., Ridoutt, B., Ugaya, C., & Hellweg, S. (2016). LCIA framework and modelling guidance [TF 1 Crosscutting issues]. In *Global guidance for life cycle impact assessment indicators* (Vol. 1, pp. 40-57). UNEP.

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Life Cycle Initiative

Global Guidance for Life Cycle Impact Assessment Indicators

Volume 1

United Nations Environment Programme

Life Cycle Initiative

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Global Guidance for Life Cycle Impact Assessment Indicators

Volume 1

Acknowledgements

Producer

This Guide has been produced by the UNEP/SETAC Life Cycle Initiative

Supervision and Support

Llorenç Milà i Canals (UNEP), Bruce Vigon (SETAC), Feng Wang (UNEP)

Editors

Rolf Frischknecht (treeze) and Olivier Jolliet (University of Michigan)

Authors

The authors are listed according to the agreement of the responsible task force. The executive summary has been prepared by the flagship co-chairs, UNEP, and the task force chairs (alphabetical order)

Executive Summary: Rolf Frischknecht (treeze), Olivier Jolliet (University of Michigan), Llorenç Milà i Canals (UNEP), Assumpció Antón (IRTA, Barcelona), Anne-Marie Boulay (CIRAIG, Canada), Francesco Cherubini (NTNU, Norway), Peter Fantke (DTU, Denmark), Annie Levasseur (Polytechnique Montréal), Thomas E. McKone (Laurence Berkeley National Laboratory), Ottar Michelsen (NTNU, Norway), Stephan Pfister (ETHZ, Switzerland), Francesca Verones (NTNU, Norway)

Chapter 1: Rolf Frischknecht (treeze), Olivier Jolliet (University of Michigan), Llorenç Milà i Canals (UNEP), Stephan Pfister (ETHZ, Switzerland), Abdelhadi Sahnoune (ExxonMobil), Cassia Ugaya (Federal Technological University of Parana, Brazil), Bruce Vigon (SETAC)

Chapter 2: Francesca Verones (NTNU, Norway), Andrew D. Henderson (US-EPA), Alexis Laurent (DTU, Denmark), Brad Ridoutt (CSRIO), Cassia Ugaya (Federal Technological University of Parana, Brazil), Stefanie Hellweg (ETHZ, Switzerland)

Chapter 3: Annie Levasseur (Polytechnique Montréal), An de Schryver (European Commission), Michael Hauschild (DTU, Denmark), Yuki Kabe (Braskem), Abdelhadi Sahnoune (ExxonMobil), Katsumasa Tanaka (National Institute for Environmental Studies, Japan), Francesco Cherubini (NTNU, Norway)

Chapter 4: Peter Fantke (DTU, Denmark), John Evans (Harvard School of Public Health), Natasha Hodas (California Institute of Technology), Joshua Apte (University of Texas), Matti Jantunen (National Institute for Health and Welfare, Finland), Olivier Jolliet (University of Michigan), Thomas E. McKone (Laurence Berkeley National Laboratory)

Chapter 5, Part A: Anne-Marie Boulay (CIRAIG, Canada), Stephan Pfister (ETHZ, Switzerland), Masaharu Motoshita (AIST, Japan), Urs Schenker (Nestlé), Lorenzo Benini (JRC European Commission), Shabbir H. Gheewala (King Mongkut's University of Technology, Thailand), Maria Clea Brito de Figueiredo (Embrapa Agroindustria Tropical, Brazil), Kevin Harding (University of the Witwatersrand, South Africa)

Chapter 5, Part B: Masaharu Motoshita (AIST, Japan), Anne-Marie Boulay (CIRAIG, Canada), Stephan Pfister (ETHZ, Switzerland), Lorenzo Benini (JRC European Commission), Maria Clea Brito de Figueiredo (Embrapa Agroindustria Tropical, Brazil), Shabbir H. Gheewala (King Mongkut's University of Technology, Thailand), Kevin Harding (University of the Witwatersrand, South Africa), Urs Schenker (Nestlé),

Chapter 6: Llorenç Milà i Canals (UNEP), Assumpció Antón (IRTA, Barcelona), Christian Bauer (SIG Combibloc), Camillo de Camillis (FAO), Ruth Freiermuth Knuchel (FOEN, Switzerland), Tim Grant (Life Cycle Strategies Pty Ltd, Australia), Ottar Michelsen (NTNU, Norway), Martha Stevenson (WWF USA)

Chapter 7: Rolf Frischknecht (treeze), Olivier Jolliet (University of Michigan), Llorenç Milà i Canals (UNEP), Stephan Pfister (ETHZ, Switzerland), Abdelhadi Sahnoune (ExxonMobil), Cassia Ugaya (Federal Technological University of Parana, Brazil), Bruce Vigon (SETAC)

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Co-Chairs: Rolf Frischknecht (treeze), Olivier Jolliet (University of Michigan)

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Editor

Jen Lynch (SETAC)

Design / Layout

Thad Mermer

Members of the task forces not present in Valencia

The authors would like to thank all members of the Task Forces that contributed to the discussions and the white papers in preparation of the Pellston Workshop® but did not attend the workshop itself. Their input significantly contributed to the achievements documented in this report.

Crosscutting issues and framework: Jane Bare, Alya Bolowich, Mattia Damiani, Jo Dewulf, Chris Koffler, Jan Paul Lindner, Xun Liao, Danielle Maia de Souza, Chris Mutel, Laure Patouillard, Massimo Pizzol, Leo Posthuma, Tommie Ponsioen, Valentina Prado, Ralph Rosenbaum, Serenella Sala, Thomas Sonderegger, Franziska Stössel, Marisa Vieira, Bo Weidema, John S. Woods

Climate change impacts: Otávio Cavalett, Jan S. Fuglestvedt, Thomas Gasser, Mark A.J. Huijbregts, Daniel J.A. Johansson, Susanne V. Jørgensen, Marco Raugei, Andy Reisinger, Greg Schivley, Anders H. Strømman

Fine particulate matter health impacts: Deborah Bennett, Otto Hänninen, Jonathan Levy, Dingsheng Li, Paul J. Lioy, Miranda Loh, Detelin Markov, Julian Marshall, Philipp Preiss, Hyeong-Moo Shin, Joseph Spadaro, Katerina Stylianou, Marko Tainio, Jouni T. Tuomisto, Charles J. Weschler

Water use impacts: Jane Bare, Markus Berger, Cécile Bulle, Michael J. Lathuillière, Alessandro Manzardo, Manuele Margni, Montserrat Núñez, Amandine Valerie Pastor, Taikan Oki, Sebastien Worbe

Land use impacts on biodiversity: Béatrice Bellini, Sharon Brooks, Jasmina Burek, Abhishek Chaudhary, Carla Coelho, Michael Curran, Maria Cléa Brito de Figueirêdo, Danielle Maia de Souza, Pieter Elshout, Simone Fazio, Jan Paul Lindner, William Puttman, Eugenie Regan, Serenella Sala, Félix Teillard, Ricardo F. M. Teixeira, Greg Thoma, Beatriz Vidal-Legaz, Matt Walpole

Contributors

The authors would like to thank everybody who has contributed to the development of the 'Global guidance for life cycle impact assessment indicators, Volume 1'. In particular, the authors would like to thank all the experts having contributed in the different task forces through the two-year long process of consensus building, as mentioned above. Also, Olivier Jolliet, Assumpció Antón, Feng Wang, Fareed Bushehri and Sophie Loueyraud for the translation of the executive summary into French, Spanish, Chinese, Arabic and Russian. Moreover, the authors would like to thank the Swiss Federal Office for the Environment (FOEN), The German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), the French Ministry of Environment, Energy and the Sea (MEEM), Rio Tinto and SIG Combibloc for providing financial support for the workshop in Valencia. The UNESCO Chair on Life Cycle and Climate Change at Escola Superior de Comerç Internacional (ESCI-UPF) provided implementation and technical support through the two years preparatory work leading to this publication. Finally, the authors would also like to thank all sponsors of the UNEP/SETAC Life Cycle Initiative (please see a complete list at the end of the publication).

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Foreword - UN Environment

Life cycle assessment is recognized as the most robust tool to provide the systems perspective required to accelerate the shift towards more sustainable consumption and production patterns. It does so by enabling the comparison between product systems (e.g. definition of "green" vs. "conventional" products), and the identification of the main hotspots driving impacts in such systems as well as of potential trade-offs among them. Indicators that clearly show the links between human interventions and environmental impacts are needed. But the pathway from human interventions to impacts can be complex, with diverse indicators being used to capture results. This reduces the comparability between studies, limiting the definition of clear preferences between products and practices, as well as the usability of results.

The *Global Guidance for Life Cycle Impact Assessment Indicators: Volume 1* goes a long way to addressing these issues. Aimed at life cycle assessment practitioners and method developers, it identifies the "current best available practice" in a variety of areas: climate change, human health impacts of fine particulate matter, water use impacts, and land use impacts on biodiversity. The global importance of these impact areas is also recognized in specific Sustainable Development Goals (SDGs).

By building consensus on indicators to represent these important impact areas, this guidance document enhances the comprehensive and consistent assessment of impacts in production and consumption systems throughout their life cycle, making explicit any potential trade-offs and supporting more sustainable processes. It provides a significant leap forward in the environmental representation and accuracy of the proposed indicators, and provides enhanced comparability among studies based on internationally endorsed, scientifically robust, and stable indicators.

The guidance is also a milestone for the UN Environment/Society for Environmental Toxicology And Chemistry Life Cycle Initiative: it positions the Initiative as a global body for the stewardship of impact assessment methods, delivering much-needed consensus-building among method developers and users. More practically, it provides the necessary access to indicators so that life cycle assessment users can incorporate them in their studies. With this publication the Initiative adds to its relevant reference documents, which have contributed to raising global awareness and capacity in life cycle approaches.

With further research and continuous improvement by the Life Cycle Initiative, these indicators will make a valuable contribution in the relevance and comparability of life cycle assessment studies, and they will ultimately enhance the accuracy of the measurement of achievement of the Sustainable Development Goals at the global level.

Ligia Noronha
Director, Division of Technology, Industry and Economics
United Nations Environment Programme

Foreword - SETAC

It is rewarding to witness the increased use of life cycle assessment (LCA) to guide decisions regarding the emergence and use of new products and technologies. As Global Executive Director for the Society of Environmental Toxicology and Chemistry (SETAC), I am well aware of the keen interest in the methodologies that have emerged from the Life Cycle Initiative (LCI), a creative and impactful effort fostered through the collaboration of SETAC and the United Nations Environmental Program (UNEP). LCA-related programs are now a part of all five of SETAC's Geographic Units: Europe, North America, Asia/Pacific, Latin America, and Africa. We have made our collaboration with UNEP a priority as evidenced by the dedication of our staff and members to LCA-related activities.

The benefits of LCA and life cycle thinking are clear. It is natural for people to view any product or technology with respect to narrow sets of benefits and costs that impact them personally. However, that narrow focus can easily miss and often diminish a broader vision of the overall environmental and health footprint. LCA helps guard against this form of myopia and enables decision makers, the public, and other stakeholders to visualize and better understand the overall profile of a particular product or technology. The shared understanding that comes with a common vision is central to fostering informed dialogues and clear pathways toward decisions that involve the various parties who may benefit and/or be affected by a product or technology. For this reason, SETAC will continue to make LCA a central component of a framework to promote the use of science and engineering to inform policy and decisions.

SETAC environmental and health scientists and engineers have focused primarily on the methodological aspects of LCA as part of the Life Cycle Initiative. While methodologies have been developed and applied with respect to the structure and functionality of LCA, it is prudent to track emerging issues that come from the learnings gained from applications and from knowledge concerning the diversity of products, technologies, and geographies for which LCA is sought as an instrument to guide decisions. In particular, the subject matter of this report is central to SETAC science. As someone that has worked in the risk assessment field for four decades, I know that methodologies continue to be updated and refined as new information emerges. And, it is my hope that there can be a convergence among methodological frameworks such as LCA and risk assessment. I share this thinking with other LCA and risk assessment practitioners. Such thinking is consistent with the growing emphasis being given to integrated assessments. As a result, I am very excited about the promise that LCA offers and the opportunity for SETAC to continue to engage with the Life Cycle Initiative to provide insights into what the future holds for the LCA approach and topical areas for applications. We are also pleased that the SETAC Pellston Workshop® format, with its rigor and well-recognized value in scientific advancement, continues to be employed by the Initiative in its work.

This document contains a reservoir of useful and practical information that reflects the dedicated effort and collaboration of many scientists, engineers, and LCA practitioners from around the globe. It should be on the physical and electronic desktops of practitioners as well as those that will benefit from and make use of the outputs of LCA.

I extend my thanks to UNEP for our successful collaborations and look forward to a continued working relationship to help promote and advance this important field of assessment. I want to thank Bruce Vigon of the SETAC staff for all of his efforts.

Charles Menzie, Ph.D.
Global Executive Director
SETAC

Abbreviations and acronyms

AGWP	Absolute global warming potential
ALRI	Acute lower respiratory infection
APEEP	Air Pollution Emission Experiments and Policy analysis
AR	Assessment report
BC	Black carbon
BR	Breathing rate
CBD	Convention on Biological Diversity
CMB	Conditions to maintain biodiversity
CF	Characterization factor
COPD	Chronic obstructive pulmonary disease
DALY	Disability-adjusted life year
ERF	Exposure-response function
FAO	Food and Agriculture Organization of the United Nations
FF	Fate factor
GBD	Global burden of disease
GHG	Greenhouse gas
GTP	Global temperature change potential
GWP	Global warming potential
HANPP	Human appropriation of net primary productivity
iF	Intake fraction
IHD	Ischemic heart disease
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
IUCN	International Union for Conservation of Nature
LC	Lung cancer
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LEAP	Livestock Environmental Assessment and Performance Partnership
LPD	Linear population density over a specified area
LU	Land use
LUC	Land use change
LULUC	Land use and land use change
MEA	Millennium Ecosystem Assessment
NPP	Net primary productivity
NTCF	Near-term climate forcer
OC	Organic carbon
PDF	Potentially disappeared fraction (of species)
PM	Particulate matter

$PM_{2.5}$	Fine particulate matter: Particles with aerodynamic diameter smaller than 2.5 µm
PNV	Potential natural vegetation
ROG	Reactive organic gas
SAR	Species-area relationship
SETAC	Society for Environmental Toxicology and Chemistry
SF	Severity factor
SOA	Secondary organic aerosol
TH	Time horizon
VOC	Volatile organic carbon
WMGHG	Well-mixed greenhouse gas
UN	United Nations
UNEP	United Nations Environment Programme
WWF	World Wide Fund for Nature
XF	Exposure factor
YLD	Years lived with a disability
YLL	Years of life lost

Executive summary

Background

Reducing the pressure on the environment related to consumption and production in human systems was identified as a priority in the 2030 Agenda for Sustainable Development by the heads of state and government, and requires the development of products and services with reduced impacts to human health and the environment. In this sense, guidance is needed on which quantitative and life cycle-based indicators are best suited to quantify and monitor man-made impacts on climate change, biodiversity, water resources, and other aspects of the biophysical environment.

Approach

In order to enhance consensus on environmental life cycle impact assessment indicators, the UNEP/SETAC Life Cycle Initiative launched a global process in 2013 focusing on four environmental topics that were selected based on their perceived environmental or political relevance, the maturity of available quantitative indicators, and the chance for reaching consensus. The goal was to reach consensus on recommended environmental indicators and characterization factors for life cycle impact assessment (LCIA) in the areas of 1) global warming, 2) fine particulate matter effects on human health, 3) water use impacts (both scarcity and human health impacts), 4) land use impacts on biodiversity, as well as 5) overall LCIA framework and crosscutting issues. International task forces worked over 24 months focusing their work on those four topics, and progress was reviewed in stakeholder engagement events around the world. White papers were prepared for each area, and previously published information was extracted into a repository for use in preparing these papers and for consultation during a final expert workshop (Pellston workshop[R]) held 24-29 January 2016 in Valencia, Spain. To ensure the validity of this guidance, workshop participants were selected for their technical expertise as well as their geographic representation and their perspective in the "life cycle thinking universe." The final mix of participants consisted of a balance of domain experts from the five topical tracks: life cycle impact assessment method developers, providers of life cycle thinking studies (primarily consultants and industry associations), and users of life cycle information, including governmental and intergovernmental organizations (IGOs), government, industry, nongovernmental organizations (NGOs), and academics.

The workshop participants emphasized developing and harmonizing environmental impact category indicators. Their discussions maintained a balance between scientific rigor and practicality to ensure the environmental indicators were credibile, applicable, and easily understood by non-scientists. It was important to bridge the gap between domain experts and indicator developers concerned with scientific complexity on one hand and users, who wanted simple, meaningful, and well-tested environmental indicators, on the other. Participants carefully defined appropriate goals and scopes for the developed indicators, and developed a glossary of terminology to enhance understanding and provide a consistent reference.

Summary results

The participants of the Pellston Workshop[R] agreed on tangible and practical recommendations on environmental indicators, including substantial innovations. The following are the main recommendations agreed upon.

Life Cycle Impact Assessment framework: The overall framework was slightly revised and now distinguishes between intrinsic, instrumental and cultural values and the damage categories human health and ecosystem quality (intrinsic), socio-economic assets, natural resources and ecosystem services (instrumental) as well as cultural and natural heritage (cultural).

Damage category indicators: The recommended damage category indicators are disability adjusted life years (DALY, human health) and biodiversity loss, including measures of vulnerability (ecosystem quality). No specific damage category indicator is recommended for natural resources and for ecosystem services at this point.

Climate change impacts: We recommend using two climate change impact categories, one representing impacts on the decadal-scale (shorter term) and another for the century-scale (longer term) impacts. The metrics from the 5th IPCC assessment report to be used are the Global Warming Potential 100 year (GWP 100) and the Global Temperature change Potential 100 years (GTP 100), respectively. We recommend using the metrics including climate-carbon cycle feedbacks for all climate forcers (so far only included for CO_2) and addressing the climate change impacts of near term climate forcers including short-lived greenhouse gases in sensitivity analyses, where GWP20 can also be used as an alternative metric for shorter-term impacts.

Fine particulate matter health impacts: Recommended characterization factors (CFs) for primary PM2.5 and interim recommended CFs secondary PM2.5 are established, which distinguish between archetypes for rural and urban areas and for indoor and outdoor emission and exposure settings. Outdoor CFs further distinguish between different emission stack heights.

Water use impacts: The impact categories for both potential ecosystem and human deprivation were discussed and further developed by the task force. Recommended CF for impacts assessing DALYs from malnutrition caused by lack of water for irrigated food production at the damage level as well as for addressing generic potential impacts of water consumption via water scarcity resulted, The native resolution of both methods is on watershed and monthly levels, but for practicability on background LCI, CF are provided also aggregated on annual, country, and global levels.

Land use impacts: CFs representing global potential species loss from land use are proposed as an interim recommendation, suitable to assess impacts on biodiversity due to land use and land use change in hotspot analyses in LCA only (not for comparative assertions nor eco-labeling). Further testing of the CFs as well as the development of CFs for further land use types are required to provide a full recommendation.

Additional crosscutting issues: Several recommendations and suggestions were formulated covering the topics of transparent reporting, reference states, spatial differentiation, uncertainties, time horizons, as well as handling of negative CF values.

Outlook and roadmap

The recommended environmental indicators should not be seen as static, but rather evolutionary and representing the current best available knowledge and practice. It is strongly recommended that the UNEP/SETAC Life Cycle Initiative fosters the momentum of cooperation and establishes a community of LCIA researchers who care for the stewardship of the recommended indicators. The community will grow with the launch of consensus finding processes for the second set of environmental impact indicators (acidification & eutrophication, human and eco-toxicity, mineral resource depletion, and ecosystem services). Spatially differentiated indicators like the ones for land use and water use call for smart and parsimonious approaches from the knowledge gained in LCA research projects in which a high geographic resolution is applied. Finally, the United Nations' Sustainable Development Goals and the concepts of planetary boundaries may profit from the work performed in this flagship project. The recommended environmental indicators may be used to quantify and monitor progress towards sustainable production and consumption.

Résumé Exécutif

Contexte

Identifié comme une priorité dans l'Agenda 2030 pour le développement durable, réduire la pression de la consommation et production mondiale sur l'environnement requiert le développement de produits et de services moins impactants sur la santé humaine et les écosystèmes. A cet effet, des lignes directrices sont nécessaires pour déterminer quels indicateurs quantitatifs conviennent le mieux dans les analyses du cycle de vie (ACV) pour quantifier et suivre les impacts créés par l'être humain sur le changement climatique, la biodiversité, les ressources en eau.

Approche

Afin de développer un consensus sur les indicateurs d'analyse de l'impact en ACV, l'Initiative pour le cycle de vie du PNUE et de la SETAC a débuté en 2013 un processus mondial se concentrant sur cinq thèmes environnementaux sélectionnés sur la base de leur pertinence environnementale et politique, de la maturité des indicateurs quantitatifs disponibles et de la probabilité de parvenir à un consensus. L'objectif était d'émettre des recommandations pour les indicateurs environnementaux et les facteurs de caractérisation d'impact dans les domaines suivants: 1) l'effet de serre, 2) les impacts des particules fines sur la santé humaine, 3) les impacts de l'utilisation de l'eau (impacts liés à la rareté de l'eau et impacts de l'utilisation de l'eau sur la santé humaine), 4) les impacts de l'utilisation des sols sur la biodiversité, ainsi que 5) le cadre d'analyse de l'impact et les questions communes à toutes les catégories d'impact. Des groupes de travail internationaux ont travaillé pendant plus de 24 mois, en concentrant leur travail sur ces cinq thèmes et leurs progrès ont été examinés par les parties prenantes lors de rencontres participatives mondiales. Des rapports ont été préparés pour chaque thème; les informations publiées précédemment ont été déposées dans un répertoire, disponible pour la préparation de ces rapports et pour consultation lors de la rencontre finale d'experts (Pellston workshopTM) qui a eu lieu à Valence (Espagne) du 24 au 29 janvier 2016. Pour assurer la validité de ces lignes directrices, les participants à cette rencontre ont été sélectionnés sur la base de leur expertise technique spécifique à chaque thème, de leur représentation géographique et de leur perspective sur les approches cycle de vie. La composition finale des participants consistait en un équilibre entre experts des cinq domaines thématiques retenus, concepteurs de méthodes d'analyse de l'impact sur le cycle de vie, prestataires d'études ACV (consultants et associations industrielles), de même que des représentants des utilisateurs des informations procurées par les ACV, comprenant des organisations gouvernementales et intergouvernementales, des gouvernements, des industries, des organisations non-gouvernementales (ONG) et des chercheurs universitaires.

L'accent a porté sur le développement et l'harmonisation d'indicateurs de plusieurs catégories d'impacts environnementaux. Toutes les discussions ont maintenu un équilibre entre rigueur scientifique et applicabilité, assurant ainsi crédibilité et facilité pour les profanes de comprendre ces indicateurs environnementaux. Une attention particulière a visé à combler le fossé entre complexité scientifique réclamée par certains experts et concepteurs d'indicateurs d'une part et la demande exprimée d'autre part par les utilisateurs de bénéficier d'indicateurs environnementaux simples, bien testés et qui font sens. L'objectif et le domaine de validité des indicateurs développés ont été soigneusement définis. Un glossaire facilite la compréhension, fournissant aux participants et lecteurs une base de référence terminologique cohérente.

Resultats

Les participants du Pellston workshop® ont approuvé des recommandations tangibles et pratiques sur plusieurs indicateurs environnementaux, apportant des innovations considérables. Les principales recommandations se résument comme suit:

Cadre d'analyse de l'impact en ACV: La structure générale a été légèrement révisée et fait maintenant la distinction entre les valeurs intrinsèques, instrumentales et culturelles d'une part et les catégories de dommages de la santé humaine et de la qualité de l'écosystème (intrinsèques),du patrimoine socio-économique, des ressources naturelles et des services écosystémiques (instrumentales) et de l'héritage culturel et naturel (culturelles) d'autre part.

Indicateurs des catégories de dommages: Les indicateurs des catégories de dommages recommandés sont les DALY (Disability Adjusted Life Years – années de vie perdues équivalentes) pour la santé humaine ainsi que la perte de biodiversité exprimée en potentiel d'espèces disparues, comprenant des mesures de vulnérabilité, pour la qualité des écosystèmes. Aucun indicateur de catégories de dommages particulier n'est recommandé à ce point pour les ressources naturelles et pour les services écosystémiques.

Impacts sur l'effet de serre: Il est recommandé d'utiliser deux catégories d'impact pour l'effet de serre, l'une représentant les impacts à plus court terme, sur une échelle de décennies, l'autre les impacts à long terme sur une échelle de plusieurs siècles. Les métriques et indicateurs retenus sont ceux proposés dans le 5ème rapport du GIEC, soit le potentiel d'effet de serre sur 100 ans (Global Warming Potential 100 year - GWP 100) et le potentiel de changement de température mondiale dans 100 ans (Global Temperature change Potential 100 years - GTP 100). Il est recommandé d'utiliser les valeurs de ces indicateurs incluant le feedback entre climat et cycle du carbone (ceux-ci n'étaient jusqu'alors compris que pour le CO2). Il est aussi recommandé d'évaluer au travers d'analyses de sensibilité les effets de serre des forceurs climatiques de très courte durée, ainsi que de tester les impacts à court terme à l'aide du GWP20.

Impacts des particules fines sur la santé: Des facteurs de caractérisation pour les $PM_{2,5}$ primaires et des facteurs de caractérisation intérimaires pour les $PM_{2,5}$ secondaires sont recommandés, distinguant entre archétypes extérieurs urbains, extérieurs ruraux et intérieurs. Les facteurs de caractérisation pour l'extérieur différencient en plus la hauteur d'émission.

Impacts de l'utilisation de l'eau: Des facteurs de caractérisation sont recommandés dans deux catégories d'impacts: un premier indicateur de rareté de l'eau caractérise les impacts potentiels de la consommation d'eau, en mesurant la privation simultanée d'eau pour les écosystèmes et la population humaine. Un second indicateur mesure en DALY les dommages sur la santé humaine dus à la malnutrition causée par le manque d'eau pour l'irrigation des cultures. La résolution originelle des deux méthodes est le bassin versant et le mois. Pour permettre la compatibilité avec les données d'inventaire actuelles, des facteurs de caractérisation agrégés sont aussi fournis au niveau annuel, par pays et au niveau mondial.

Impacts de l'utilisation des sols: Des facteurs de caractérisation correspondant à la perte potentielle totale d'espèces due à l'utilisation des sols sont proposés comme recommandation intérimaire. Ils sont adaptés à l'évaluation des impacts de l'utilisation des sols ainsi que des changements d'utilisation sur la biodiversité afin d'identifier les points sensibles d'une chaîne de production donnée. Ils ne sont pas applicables pour des assertions comparatives ou pour l'éco-étiquetage. Des tests ultérieurs sur ces facteurs de caractérisation, de même que le développement de facteurs de caractérisation pour d'autres types d'utilisation des sols sont nécessaires pour aboutir à une recommandation finale.

Questions transversales supplémentaires: Plusieurs recommandations et suggestions ont été formulées sur des sujets tels que la publication de rapports transparents, les états de référence, la différenciation spatiale, les incertitudes, les horizons de temps et le traitement des valeurs négatives de facteurs de caractérisation.

Perspectives et feuille de route

Les indicateurs environnementaux recommandés ne devraient pas être considérés comme immuables mais plutôt comme faisant partie d'un processus évolutif, ils reflètent les meilleures connaissances et pratiques actuellement disponibles. Il est fortement recommandé que l'Initiative pour le cycle de vie du PNUE et de la SETAC tire profit du dynamisme du présent projet pour établir une communauté de chercheurs en analyses de l'impact sur le cycle de vie qui veille à la bonne gestion et à la mise à jour régulière des indicateurs recommandés. Cette communauté va encore s'étendre avec le lancement d'un second processus de recherche de consensus pour une deuxième série d'indicateurs d'impacts environnementaux pour l'acidification et l'eutrophication, la toxicité humaine et l'écotoxicité, l'épuisement des ressources minérales ainsi que les services écosystémiques. Le développement d'indicateurs différenciés spatialement, comme ceux retenus pour la caractérisation de l'utilisation des sols et de l'eau, nécessitent des approches adéquates et parcimonieuses se basant sur les projets de recherche en ACV dans lesquels une haute résolution géographique est utilisée. Finalement, les Objectifs de développement durable des Nations Unies et les concepts de limites planétaires pourront tirer profit du travail accompli dans ce projet phare. Les indicateurs environnementaux recommandés peuvent être employés pour quantifier et suivre les progrès effectués en vue d'une production et consommation durables.

Resumen ejecutivo

Antecedentes

Garantizar modalidades de consumo y producción sostenibles ha sido identificado como una prioridad en la Agenda 2030 para el Desarrollo Sostenible. En este sentido para una mejor gestión de la problemática ambiental, se hace necesario disponer de indicadores consensuados de ciclo de vida para optimizar la cuantificación y monitoreo de los impactos humanos sobre distintas categorías de impacto ambientales: cambio climático, pérdida de biodiversidad, sobreexplotación de recursos de agua, etc.

Enfoque

Con el fin de mejorar el consenso sobre los indicadores de evaluación de impactos ambientales de ciclo de vida, la UNEP/SETAC Life Cycle Initiative emprendió, en el año 2013, un proceso centrado en proporcionar guía en la utilización de indicadores ambientales, seleccionados en función de su relevancia medioambiental y política, así como de la madurez y disponibilidad de los indicadores cuantitativos existentes. El objetivo era llegar a un consenso sobre los indicadores ambientales y factores de caracterización recomendados para la Evaluación de Impactos del Ciclo de Vida (EICV) en las categorías de impacto de: 1) calentamiento global, 2) efectos en la salud humana de emisiones de micropartículas, 3) los impactos del uso del agua (tanto la escasez como impactos sobre la salud humana), 4) impactos del uso de la tierra sobre la biodiversidad, así como 5) marco general de LCIA y temas transversales. Grupos de trabajo internacionales trabajaron durante más de 24 meses centrándose en esos cinco temas, el progreso se revisó en eventos de consulta con partes interesadas alrededor del mundo. Con la información recopilada se prepararon libros blancos para cada área, que sirvieron de base en el taller de expertos final (Pellston WorkshopTM) celebrado en Valencia (España) del 24 al 29 de enero de 2016. Para asegurar la validez de esta guía, se seleccionaron los participantes del taller por sus conocimientos técnicos, así como su representación geográfica y su probada experiencia alrededor del enfoque de "ciclo de vida." La composición final de los participantes ofrece un equilibrio de expertos en el dominio de los cinco temas objeto de debate, creadores de métodos de evaluación de impactos en el marco de los estudios de ciclo de vida, proveedores de estudios de análisis de ciclo de vida (principalmente consultores y asociaciones industriales), junto con los usuarios de la información de ciclo de vida, incluidas organizaciones gubernamentales e intergubernamentales (OIG), gobiernos, industria, organizaciones no gubernamentales (ONG) y académicos.

Se hizo hincapié en el desarrollo y la armonización de los indicadores de categoría de impacto ambiental. Las discusiones mantuvieron un equilibrio entre el rigor científico y el sentido práctico para asegurar así la credibilidad, la aplicabilidad y la facilidad de comprensión de los indicadores por parte de no expertos. Se tuvo especial cuidado en aproximar, por un lado, la complejidad científica reclamada por los expertos, y la demanda por parte de los usuarios de indicadores simples, útiles y bien probados por el otro. Así mismo se definieron cuidadosamente el objetivo y alcance para los cuales se consideran apropiados los indicadores desarrollados. Para mejorar la comprensión, uno de los ejercicios del taller fue desarrollar un glosario de términos para proporcionar una base coherente de referencia para los participantes, así como para los lectores.

Resumen de resultados

Los participantes del Pellston WorkshopTM acordaron recomendaciones tangibles y prácticas sobre los indicadores ambientales, incluyendo innovaciones sustanciales. Las siguientes son las principales recomendaciones acordadas.

Marco de la Evaluación de Impactos del Ciclo de Vida (EICV): El marco general de EICV fue revisado distinguiéndose entre valores intrínsecos, instrumentales y culturales, así como las categorías correspondientes a daño a la salud humana y a la calidad del ecosistema (valores intrínsecos), activos socio-económicos, recursos naturales y servicios ambientales (instrumentales), y patrimonio cultural y natural (culturales).

Indicadores de daño: Los indicadores de evaluación del daño en salud humana recomendados son los años de vida perdidos por enfermedad o muerte prematura (también conocidos como años de vida ajustados por discapacidad, AVAD o DALY en inglés). En el caso de evaluación de daño en la calidad del ecosistema se recomienda utilizar la pérdida de biodiversidad, incluyendo medidas de la vulnerabilidad . Por el momento no hay indicador de daño recomendado para la pérdida de los recursos naturales y servicios del ecosistema.

Impactos del cambio climático: Se recomienda el uso de dos indicadores para la categoría de impacto del cambio climático, uno en representación de los impactos a escala de décadas (corto plazo) y otra para los impactos a escala del siglo (largo plazo). Las métricas del 5o informe de evaluación del IPCC a utilizar son el Potencial de Calentamiento Global de 100 años (GWP 100) y el cambio de temperatura potencial global de 100 años (GTP 100), respectivamente. Se recomienda utilizar dichas métricas incluyendo procesos de retroalimentación clima-ciclo del carbono para todos los Gases de Efecto Invernadero (GEI) (por el momento sólo se incluyen para el CO_2). También se recomienda considerar los impactos del cambio climático de GEI de corto plazo, incluyendo gases de efecto invernadero de corta duración en los análisis de sensibilidad, donde GWP20 también puede ser utilizado como una unidad de medida alternativa para los impactos a corto plazo.

Impactos sobre la salud causados por micropartículas: Se recomiendan FC para PM2,5 primarias y se sugiere una recomendación provisional para $PM_{2.5}$ secundarias. Dichos FC distinguen entre arquetipos para zonas rurales y para zonas urbanas, así como para las emisiones y exposición en interior y en exteriores. Los FC al aire libre distinguen además entre diferentes alturas de emisión.

Impactos del uso de agua: Se discutieron y desarrollaron dos categorías de impacto. Por un lado se proporcionan FC recomendados para evaluar DALYs a nivel de daño por desnutrición, causada por la falta de agua para la irrigación de los cultivos. Por otro se sugieren FC de escasez hídrica para abordar los impactos potenciales genéricos del consumo de agua, cubriendo tanto daño potencial a ecosistemas como de privación humana. La resolución geotemporal de ambos métodos es de cuenca hidrográfica y mensual, pero para asegurar la viabilidad en caso de información de segundo plano, se proporcionan también FC agregados a nivel anual, nacional y mundial.

Impactos del uso del suelo: Se recomiendan provisionalmente FC que representan la pérdida potencial global de especies debida al uso del suelo; estos FC son adecuados para evaluar los impactos sobre la biodiversidad debido a la utilización del suelo y el cambio del uso del suelo en el análisis de puntos conflictivos en ACV (no resultando adecuados para las aseveraciones comparativas ni el etiquetado ecológico). La recomendación completa se podrá realizar a partir de más estudios con los FC, así como el desarrollo de FC para otros tipos de uso del suelo.

Temas transversales adicionales: se formularon varias recomendaciones y sugerencias sobre los temas de informes transparentes, estados de referencia, diferenciación espacial, incertidumbre, horizontes temporales, así como la manipulación de CF negativos.

Outlook y hoja de ruta

Los indicadores ambientales recomendados no deben ser considerados como algo estático sino de carácter evolutivo, representando el mejor conocimiento y práctica actual disponibles. Se recomienda encarecidamente que la UNEP/SETAC Life Cycle Initiative aproveche el impulso de cooperación y establezca una comunidad de investigadores EICV que cuiden de la gestión de los indicadores recomendados. Dicha comunidad va a expandirse con el inicio de la búsqueda de consenso para el segundo conjunto de indicadores de impacto ambiental: acidificación y eutrofización, toxicidad humana y eco-toxicidad, agotamiento de recursos minerales y servicios de los ecosistemas. Los indicadores con una clara diferenciación regional como por ejemplo los de uso del suelo y el uso del agua requieren de enfoques que equilibren complejidad y practicidad, enfoques que pueden verse beneficiados de los conocimientos adquiridos en estudios previos de ACV en los que se aplica una alta resolución geográfica. Por último, los Objetivos de Desarrollo Sostenible de las Naciones Unidas y los conceptos de límites planetarios pueden beneficiarse del trabajo realizado en este proyecto. Los indicadores ambientales recomendados pueden ser utilizados para cuantificar y controlar el progreso hacia la producción y el consumo sostenibles.

Резюме

Контекст

Уменьшение воздействия на окружающую среду человеческими системами из-за потребления и производства, является одним из приоритетов Целей в области устойчивого развития на период до 2030г. Для достижения этих целей требуется разработка товаров и услуг, оказывающих меньшее воздействие на здоровье человека и окружающую среду. Для этого, необходимо руководство о том, какие количественные показатели и какие показатели, основанные на концепции жизненного цикла лучше подходят к количественной оценке и мониторингу антропогенного воздействия на изменение климата, биоразнообразия, водные ресурсы и т.д.

Подход

С 2013 года, «Инициатива по жизненному циклу», разработанная Программой Объединённых Наций по Окружающей среде и Обществом по экологической токсикологии и химии (СЕТАК, по его английскому названию), предприняла глобальный процесс, сосредоточившись на четырех экологических темах, выбранных на основе их предполагаемой экологической или политической значимости, завися от совершенства существующих количественных показателей и от вероятности достижения консенсуса. Главная цель самого процесса является согласованием рекомендуемых экологических показателей и характеризующих факторов по оценке воздействия на окружающую среду, основанных на концепции жизненного цикла (LCIA - ЛКИА по его английскому названию), в областях 1) глобального потепления, 2) воздействия мелких твердых частиц на здоровье человека, 3) последствия водопотребления (в связи и с его воздействием на здоровье человека и с дефицитом воды), 4) воздействия землепользования на биоразнообразие, а также 5) определения общей рамки для ЛКИА и точек пересечения между всеми этими тематиками.

Международные рабочие группы работали над четырьмя тематиками на протяжении двух лет. Прогресс последовательно оценивался в ходе мероприятий, организованных по всему миру и нацеленных на вовлечение компетентных сторон. Для каждой тематики были разработаны «Белые бумаги», также, была собрана информация о более ранних публикациях. Эта база данных была представлена экспертам в течении консультации, которая была проведена во время заключительного семинара экспертов (Pellston workshopTM), состоявшегося в Валенсии (Испания) с 24 ого до 29ого января 2016 года. Чтобы увериться в обоснованности данных руководств, участники семинара были отобраны согласно их техническим знаниям, географической представленности, и их знаниям о "мышлении по жизненному циклу". Набор участников оказался достаточно уравновешенным: сотрудничали эксперты со специализациями в пятерых тематиках, разработчики методов ЛКИА, а также, исследователи по мышлению жизненного цикла (в основном, консультанты и отраслевые ассоциации). Пользователи информацией о жизненном цикле тоже принимали участие (в том числе, правительственные и межправительственные организации (МПО), правительства, промышленные представители, неправительственные организации (НПО) и научные круга).

Особое внимание было уделено разработке и гармонизации категоричных показателей по воздействию на окружающую среду. Все эти дискуссии учитывали и научную строгость, и практичность, таким образом, обеспечивая доверие, применимость и легкость понимания неспециалистами. Было необходимо объединить, с одной стороны, сложность научных понятий, и, с другой стороны, простоту применения экологических показателей. Были предприняты усилия, чтобы тщательно определить цели и области применения, подходящие для показателей. Для более глубокого понимания этих тем, одно из упражнений семинара заключалось в разработке терминологического глоссария (чтобы обеспечить последовательную ссылку для участников, а также для читателей).

Итоговые результаты

Участники в Пельстон семинаре (Pellston Workshop®) договорились о материальных и практических рекомендациях по экологическим показателям, в том числе о существенных нововведениях. Ниже предлагаются главные рекомендации, согласованные в курсе семинара.

Рамка по оценке воздействия на окружающую среду, основанная на концепции жизненного цикла. Общая структура была немного пересмотрена, и вследствие, в данный момент, состоит из показателей по оценке повреждения на здоровье человека и качество экосистем, по оценке социально-экономических преимуществ, природных ресурсов, экосистемных услуг, а также, по оценке культурного и природного наследия.

Категоричные показатели по оценке ущерба: рекомендуемыми показателями по оценке ущерба являются "скорректированная продолжительность жизни из-за инвалидности" (DALY – ДАЛИ по английскому названию, и здоровье человека), утрата биоразнообразия, в том числе уровень уязвимости биоразнообразия. В данный момент, не рекомендуется определять показателей по оценке ущерба по отношению к природным ресурсам и экосистемным услугам.

Последствия изменения климата: Рекомендуется использовать две категории индикаторов для измерения последствий изменения климата, одна - представляющая воздействие на десятилетнем периоде (кроткий срок), а другая – воздействие на вековом периоде (долгий срок). Метриками из Пятого доклада об оценке МГЭИК, которые должны быть использованы, являются «Потенциальное глобальное потепление на 100 лет (ГВП100 – «GWP 100» по английскому названию)» и «Потенциальное глобальное изменение температур на 100 лет (ГТП100 – «GTP 100» по английскому названию). Рекомендуется использовать метрики, включающие обратные связи между климатическо-углеродным циклом и всеми факторами, влияющими на изменение климата (до сих пор, только включены те, относящиеся к CO2). Кроме того, рекомендуется работать над преодолением последствий изменения климата (ближайшая перспектива), в том числе над короткоживущими парниковыми газами. Это может быть сделано с помощью анализов чувствительности, в которых GWP20 (ГВП20) также может быть использован в качестве альтернативного показателя по краткосрочному воздействию.

Мелкие частицы и их воздействие на здоровье человека: рекомендуемые характеризующие факторы (CF— КФ по английскому названию) по оценке воздействия первичного PM2.5 и временно рекомендуемые КФ по оценке воздействия вторичного PM2.5 различаются по архетипам сельских и городских районов, по внутренним и наружным выбросам и излучениям. Наружные КФ далее различаются согласно с разными степенями выбросов.

Воздействие водопотреблениея: две категории воздействия было обсуждено и дальше разработано рабочей группой. Это привело к КФ, которые рекомендуют оценивать воздействия ДАЛИ, из-за недоедания, вызванного нехваткой воды для орошаемого производства пищевых продуктов, а также для решения общих потенциальных последствий водопотребления, сосредоточиваясь на решение дефицита водных ресурсов, с целью решить потенциальные недостатки ресурсов для экосистемы и человека. Данные, собранные в рамке обоих методов, сосредоточены на оценку водораздела и месячного уровня, но имея в виду цель оптимальной практичности ЛКИ, КФ также предлагаются в виде сводных данных ежегодно, на национальном, и на глобальном уровне.

Земельное использование: КФ, оценивающие глобальное потенциальное исчезновение видов из-за землепользования, предложены в качестве временной рекомендации, подходящей для оценки воздействия на биоразнообразие, происходящего от землепользования, исключительно в ЛКА анализах по горячим точкам (но не для сравнительного утверждения, ни экомаркировки). Для представления окончательных рекомендаций, требуются дальнейшее тестирование КФ, а также развитие КФ для дальнейших видов землепользования.

Дополнительные вопросы касающиеся работы в общем: были сформулированы рекомендации и предложения, касающиеся следующих тем: прозрачная отчетность, система эталонов, пространственная дифференциация, неопределенность, временные горизонты, а также, обработка отрицательных значений CF.

Перспективы и дорожная карта

Рекомендации об экологических показателях следует принимать не как статические, а скорее, как эволюционные показатели, которые отражают в настоящем времени наилучшие имеющиеся в распоряжении знания и практики. Необходимо, чтобы Инициатива ЮНЕП СЕТАК по жизненному циклу способствовала импульсу сотрудничества и учредила сообщество исследователей по ЛКИА, заботящихся о дальнейшем развитии рекомендуемых показателей. Сообщество будет расти с запуском процессов, поощряющих достижение консенсуса относительно второго набора показателей по воздействию на окружающую среду (токсичность для человека и окружающей среды, истощение минеральных ресурсов и экосистемных услуг, и т.д.). Такие пространственно- дифференцированные показатели, как те, используемые по землепользованию и водопользованию, призывают к умным и экономным подходам. И это, благодаря знаниям, полученным от исследовательских проектов по оценке жизненного цикла, в которых применяется географическая перспектива. И, наконец, этот флагманский проект может способствовать достижению Целей устойчивого развития Организации Объединенных Наций и концепции планетарных границ. Рекомендуемые экологические показатели могут быть использованы для количественной оценки и мониторинга в области устойчивого производства и потребления.

执行摘要

背景

在2030可持续发展议程中，减少人类系统在消费和生产过程所产生的环境压力是其中的一项工作重点。这项工作需要在开发产品和服务的过程中，减少对人类健康和环境的影响。建立生命周期评价指标有利于定量评估和监控人类活动对于气候变化、生物多样性、水资源等方面的影响。因此针对这些指标，我们需要建立相关的指南。

方法

为了达成环境影响评价指标的共识，the UNEP/SETAC Life Cycle Initiative（联合国环境规划署与环境毒理与化学协会所建立的生命周期倡议计划）在2013年开展了一项针对四项环境问题的全球研讨过程。这个过程基于环境影响评价指标的环境影响、政策相关性、现有定量指标的成熟度、以及达成共识的可能性进行了研讨和总结。这项工作的目的是针对生命周期环境影响评价过程中，所涉及的环境指标和特征化因子达成共识并推荐统一的标准。目前，该项目涵盖了以下五个方面的指标：1）全球变暖；2）微小颗粒物对人类健康的影响；3）水资源的使用影响（包括水资源稀缺性和对人类健康的影响）；4）土地利用对生物多样性的影响；5）环境影响评价的整体框架和跨领域问题。

不同的国际工作组用了2年多时间在这几项问题领域上进行了充分的研究，与此同时，项目在全世界范围内召集了利益相关者开展了研讨会，对研究的进展和成果进行了充分的评估。针对每一个问题领域，工作组整合以前所发表过的信息生成一个知识库，并且准备了一份白皮书，为2016年一月在西班牙瓦伦西亚所举行的专家研讨会（Pellston workshop™）作准备。为了确保这项指南的有效性，这次专家研讨会针对专家的区域代表性和专家在生命周期评价领域的建树进行了谨慎的筛选。在最终的专家名单中，我们邀请了五个问题领域的相关专家、生命周期影响评价方法的开发人员、生命周期思想研究（主要为专业顾问和工业协会）、以及生命周期信息的使用者（包括政府组织和政府间组织、政府、工业界、非政府组织和学术界）。

这个研讨会的重点是发展和统一每个问题领域中相应的环境影响指标。所有的讨论都试图在科学的严谨性和实际应用性中寻找到一个平衡，这可以确保环境指标能容易地被没有相关专业背景的人员使用。我们在建立指标的过程中，充分考虑到（相关领域专家以及指标开发人员所要求）科学复杂性和用户需要简单的、有意义的、经过反复测试和验证的环境指标，并在两者之间建立平衡。这个过程中，专家们谨慎地界定指标的目标和使用边界。为了增强理解，研讨会一项重要的内容是针对专家和本报告的读者，建立了一套可以用于文献连贯引用的术语定义表。

成果总结

Pellston Workshop™专家研讨会的成员针对环境影响评价指标，达成了有效和实用的建议，并且在这个过程中实现了很大的创新。以下列出专家达成共识的主要建议：

生命周期影响评价框架：整体的框架进行了微小的修改之后，目前能够区别内在的、功能性的、文化价值、损害类型指标（人类健康和内在的生态系统质量）、社会经济价值、自然资源和生态系统服务功能以及文化和自然遗产。

损害类型指标：本报告推荐的损害类型指标包括伤残调整寿命年（DALY，人类健康）和生物多样性损失（包括衡量生态系统质量的脆弱性）。对于自然资源和生态系统服务，目前还没有推荐的损害类型指标。

气候变化影响：本报告推荐使用两项气候影响类别。一项代表十年尺度（短期）和一项代表百

年尺度（长期）的影响。政府间气候变化专门委员会的《第五次评估报告》分别推荐了使用百年全球变暖潜能值(GWP 100)和百年全球温度变化潜能值（GTP 100）。本报告推荐使用包括针对所有气候强迫因子 （目前仅包括二氧化碳 ）的气候一碳循环响应衡量标准。本报告也同时推荐涉及近期气候强迫因子（包括对短寿命温室气体的敏感度分析）对气候变化的影响，在这种情况下，GWP20可以做为短期影响评价的替代指标。

细颗粒物对健康的影响：建立了推荐的针对一级$PM_{2.5}$，和临时推荐的特征化因子二级$PM_{2.5}$的 特征化因子。这些特征化因子区别对待城市和郊区地区、室内和室外排放、以及暴露设置的模型。与此同时，室外特征化因子区别可以不同的烟囱排放高度。

水资源利用影响：讨论和开发了两个影响类别，最终推荐了由营养不良导致的DALYS特征化因子，这些影响是由于缺少水资源对食物生产灌溉以及针对水资源消耗（水资源的稀缺性对生态环境和人类的影响）所产生的。两种方法的精确度针对每月的流域数据，但从背景环境清单的可操作性出发，推荐的特征化因子在年度、国家、和全球层面进行了汇总。

土地利用影响：本报告推荐了代表由土地利用所导致的全球潜在物种减少的特征化因子，这个特征化因子仅针对于生命周期评价的热点分析，做为临时特征化因子评估土地利用和土地利用变化对生物多样性影响所推荐使用。为了推荐全面的指标，未来需要针对土地利用类型的特征化因子进行深度的测试和开发。

额外的跨领域交叉问题：针对报告的透明度、基准状态、空间差异、不确定性、时间跨度、以及处理特征化因子的负值，本报告提供了一些相关的建议和指导。

展望与实施路线

本报告所推荐的环境指标并不是静态的，他们是革命性的并且代表了当前最前沿的知识和实践经验。我们强烈建议生命周期倡议计划利用本次合作的契机，为从事生命周期环境影响评价的学者们创立一个合作平台。这个平台在今后推荐使用相关的生命周期环境影响评价指标中能够不断完善，并且在第二阶段推荐其他的指标（酸化和富营养化、人类毒性和生态毒性、矿产资源消耗、生态系统服务）。在空间上有区别的指标（比如土地利用和水资源利用）需要更加智能和简便的方法，这些方法可以从一些具有高地理解析度的生命周期评价项目中获取经验。最终，联合国可持续发展目标和地球边界理念可以从个项目中受益。这个报告中所推荐的环境指标可用于定量分析并监控可持续生产和消费的进度。

Executive summary (Arabic)

مؤشرات فئة الضرر: :مؤشرات فئة الضرر الموصى بها هي سنوات العجز المعدلة (سنوات العمر المصححة حسب العجز دالي، وصحة الإنسان)، وفقدان التنوع البيولوجي، بما في ذلك تدابير الضعف (جودة النظم الإيكولوجية). ولم يوصى بأي مؤشر فئة الضرر على الموارد الطبيعية وخدمات النظم الإيكولوجية في هذه المرحلة.

آثار تغير المناخ: من المستحسن استخدام فئتان لتأثير تغير المناخ، واحد يمثل التأثر على مقياس العقدية (المدى القصير) والآخر التأثر على مقياس القرن (المدى البعيد). أن المقاييس التي يجب إستخدامها من التقرير الخامس لتقييم تغير المناخ لفريق البين الحكومي المختص بالتغير المناخي هي ظاهرة الاحتباس الحراري المحتملة 100عام (GWP 100) واحتمالية تغير درجة الحرارة العالمية خلال 100سنة (GTP 100)، على التوالي. فمن المستحسن استخدام المقاييس بما في ذلك ردود دورة المناخ لجميع قوى (والتي شملت ثاني أكسيد الكربون حتى الآن فقط). ويوصى أيضا لمعالجة آثار تغير المناخ من قوى المناخ على المدى القريب بما في ذلك الغازات المسببة للاحتباس الحراري قصيرة الأجل في تحليل الحساسية، حيث يمكن أن تستخدم أيضا GWP20 باعتبارها مقياسا بديلا للآثار على المدى القصير.

الآثار الصحية للجسيمات الدقيقة: تقررت عوامل توصيف الموصى بها للجسيمات الأولية أقل من 2.5 ميكرون والمؤقتة أقل من 2.5 ميكرون والتي تميز بين الأمثلة للمناطق الريفية والحضرية وضبط الانبعاثات والتعرض في الأماكن المغلقة والهواء الطلق. و يميز عامل توصيف الهواء الطلق بين مختلف إرتفاعات مداخن الانبعاثات.

آثار إستخدام المياه: تم مناقشة فئتين من المؤثرات وتطويرهما من قبل فريق العمل والذي أدى إلى التوصية بإستخدام عامل توصيف لآثار سنوات العمر المصححة حسب العجز من سوء التغذية الناجم عن نقص المياه لإنتاج الغذاء المروية على مستوى الضرر وكذلك لمعالجة الآثار المحتملة الأخرى من استهلاك المياه عبر ندرة المياه، ومعالجة كل، النظام البيئي المحتمل والحرمان البشري. والقرار الأصلي من كلتا الطريقتين على مستجمعات المياه والمستوى الشهري، ولكن للتطبيق العملي على خلفية أثر دورة الحياة، يتم توفير تجميع عامل توصيف سنوي، على المستوى القطري والعالمي.

آثار استخدام الأراضي: تمثل عوامل التوصيف احتمالية عالمية لفقدان التنوع بسبب إستخدام الأراضي وتم إقتراح توصية مؤقتة مناسبة لتقييم التأثيرات على التنوع البيولوجي نتيجة لاستخدام الأراضي وتغيير استخدام الأراضي في بؤرة التحليل في تقييم دورة الحياة فقط (وليس لتأكيدات المقارنة ولا وضع العلامات الإيكولوجية). ويلزم إجراء مزيد من التجارب من العوامل توصيف فضلا عن تطوير عوامل توصيف لمزيد من أنواع استخدام الأراضي لتوفير توصية كاملة.

قضايا شاملة إضافية: تم صياغة العديد من التوصيات والمقترحات التي تغطي مواضيع تقارير تتسم بالشفافية، الدول المرجعية، والتمايز المكاني، وعدم اليقين، الآفاق الزمنية، وكذلك التعامل مع قيم معامل التوصيف السلبي.

التوقعات وخارطة الطريق

لا ينبغي أن ينظر إلى المؤشرات البيئية الموصى بها كثوابت بل هي كونها تطورية نوعا ما، وتمثل أفضل المعارف والممارسات المتاحة الحالياً. وتوصى مبادرة دورة الحياة المدارة من قبل برنامج الأمم المتحدة للبيئة وجمعية علم السموم البيئية والكيمياء بشدة بتبني الزخم للتعاون وتحديد مجموعة من الباحثين في تقييم أثر دورة الحياة الذين يهتمون في قيادة هذه المؤشرات الموصى بها. وأن المجتمع ينمو مع إطلاق عمليات إجماع الحقائق عن المجموعة الثانية من مؤشرات الأثر البيئي (التحمض والإثراء الغذائي، والبشرية وسمية البيئية، واستنزاف الموارد المعدنية وخدمات النظام الإيكولوجي). إن المؤشرات المتباينة مكانيا مثل استخدام الأراضي واستخدام المياه تدعوة لمنهج ذكي وشحيح جدا من المعرفة المكتسبة في مشاريع بحثية تقييم دورة الحياة والتي تطبق حلول جغرافية عالية. وأخيرا، قد تستفيد أهداف التنمية المستدامة التابعة للأمم المتحدة ومفاهيم حدود الكواكب من العمل المنجز في هذا المشروع الرائد. ويمكن استخدام المؤشرات البيئية الموصى بها لقياس ورصد التقدم المحرز نحو الإنتاج والاستهلاك المستدام.

1. الملخص التنفيذي

الخلفية

أن الحد من الضغط على البيئة المرتبط بالاستهلاك والإنتاج في النظم البشرية والذي تم تحديدة كأولوية في جدول أعمال 2030 للتنمية المستدامة، يتطلب تطوير منتجات وخدمات قليلة الآثر على صحة الإنسان والبيئة . وفي هذا السياق، هناك حاجة إلى التوجيه لتحديد أنسب المؤشرات الكمية والمبنية على دورة الحياة والتي تقيس وترصد آثار ما صنعة الإنسان على تغير المناخ والتنوع البيولوجي والموارد المائية، الخ.

النهج

من أجل تعزيز توافق في الآراء بشأن مؤشرات تقييم الأثر دورة الحياة البيئية، بدأ برنامج الأمم المتحدة للبيئة ومبادرة دورة الحياة لجمعية علم السموم البيئية والكيمياء عملية عالمية في عام 2013 والتي ركزت على أربعة مواضيع بيئية مختارة على أساس أهميتها البيئية أو السياسية، لتصورنضج المؤشرات الكمية المتاحة، فضلا عن فرص التوصل إلى توافق في الآراء . وكان الهدف هو التوصل إلى توافق في الآراء بشأن المؤشرات البيئية الموصى بها وعوامل توصيف تقييم أثر دورة الحياة في مجالات 1) الاحتباس الحراري، 2)تأثير الجسيمات الصغيرة على صحة الإنسان، 3) آثار استخدام المياه (سواء على ندرة المياه أوتأثيراتها على صحة البشر) 4) آثار استخدام الأراضي على التنوع البيولوجي وكذلك 5) إطار دورة الحياة الشاملة وتقييم الأثر والقضايا المشتركة . وعملت فرق العمل الدولية على مدى 24 شهرا مركزة عملها على تلك المواضيع الأربعة، وخضع التقدم المحرز لمراجعة من خلال لقاءات إشراك أصحاب المصلحة في جميع أنحاء العالم. تم إعداد تقارير شاملة لكل موضوع، واستخراج المعلومات المنشورة مسبقا واستيداعها لاستخدامها في إعداد هذه الأوراق وللتشاور خلال ورشة عمل الخبراء النهائية (ورشة عمل بيلستون) والذي عقد في فالنسيا (اسبانيا) في 24 29 يناير2016. ولضمان صحة هذا التوجهه، تم اختيار المشاركين في ورشة العمل بناءً على خبراتهم التقنية، وكذلك التمثيل الجغرافي كذلك وجهة نظرهم في "التفكير الشامل حول دورة الحياة". وأن المزيج النهائي للمشاركين تألف من توازن بين الخبراء في نطاق المسارات الموضعية الخمسة، مطوري تقييم أثر دورة طرق الحياة، ومقدمي دراسات حول تفكير دورة الحياة (في المقام الأول الاستشاريين والاتحادات الصناعية) جنبا إلى جنب مع مستخدمي معلومات دورة الحياة، بما في ذلك المنظمات الحكومية والمنظمات البينية الحكومية، والحكومة والصناعة والمنظمات غير الحكومية والأكاديميين.

وكان التركيز على تطوير وتنسيق فئات مؤشرات الأثر البيئي . وحافظت كل هذه المناقشات على التوازن بين الدقة العلمية والعملية، وبالتالي ضمان مصداقية وإمكانية التطبيق وسهولة فهم المؤشرات البيئية من قبل الناس العاديين. وإتخذت عناية خاصة لتقريب الوجهات بين التعقيد العلمي والتي يطالب به خبراء النطاق ومطوري المؤشرات من جهة ودعوة المستخدمين لمؤشرات بيئية مبسطة، ذات مغزى ومختبرة بشكل جيد من جهة أخرى. و بذلت الجهود لتحديد دقة الأهداف والمجالات التي على أساسها قد وضعت المؤشرات ومدى ملائمتها. و لتعزيز التفاهم، تم تخصيص واحدة من تمارين ورشة العمل لتطوير معجم المصطلحات لتوفير أساس ثابت مرجعية للمشاركين وكذلك للقراء.

ملخص النتائج

اتفق المشاركون في ورشة عمل بيلستون على توصيات ملموسة وعملية حول المؤشرات البيئية، بما في ذلك ابتكارات كبيرة . وفيما يلي أهم التوصيات المتفق عليها.

إطار تقييم أثر دورة الحياة: تم تنقيح الإطار العام قليلا ويميز الآن بين القيم الجوهرية، القيم الفعالة والثقافية والفئات متضررة مثل صحة الإنسان ونوعية النظام البيئي (القيم الجوهرية)، والأصول الاجتماعية والاقتصادية والموارد الطبيعية (القيم الفعالة) وكذلك التراث الثقافي والطبيعي (القيم الثقافية).

1. Motivation, Context and Overview

Rolf Frischknecht, Olivier Jolliet, Llorenç Milà i Canals, Stephan Pfister, Abdelhadi Sahnoune, Cassia Ugaya, Bruce Vigon

1.1 Setting the scene and objectives

According to the United Nations' Millennium Goals Road Map Report (United Nations 2001), it is one of our greatest challenges in the coming years to ensure that our children and all future generations are able to sustain their lives on the planet. If we do not act now, and try to contain the damage already done and mitigate future harm, we will inflict irreversible damage to our environment. The report identifies climate change, preserving biodiversity, as well as managing forest and water resources as priority issues. The goals were revisited and fixed in a resolution of the United Nations' General Assembly on Sustainable Development Goals (United Nations 2015).

The current pressures on the environment and, especially, our need to reduce them in the coming years require us to develop green products and services. Because markets and supply chains are increasingly globalized, harmonized guidelines are needed on how to quantify the environmental impacts of products and services. In particular, guidance is needed on which quantitative and life cycle based indicators are best suited to quantify and monitor the man-made impacts on climate change, biodiversity, water resources, etc. Stakeholders in industry and public policy thus agree on the need for consensus on environmental life cycle impact assessment indicators.

As stated in Jolliet et al. (2004), "Life Cycle Impact Assessment (LCIA) methods aim to connect, to the extent possible, emissions and extractions quantified in life cycle inventories (LCI-results) on the basis of impact pathways to their potential environmental damages. Impact pathways consist of linked environmental processes, and they express the causal chain of subsequent effects originating from an emission or extraction. According to ISO [International Organization for Standardization (ISO) 2006], LCI results are first classified into impact categories. A category indicator, representing the amount of impact potential, can be located at any place between the LCI results and the category endpoint."

Based on the LCIA framework, different approaches have developed over time, with midpoint (impact) or damage oriented indicators at different levels of the cause-effect chains. Alternative methods are available

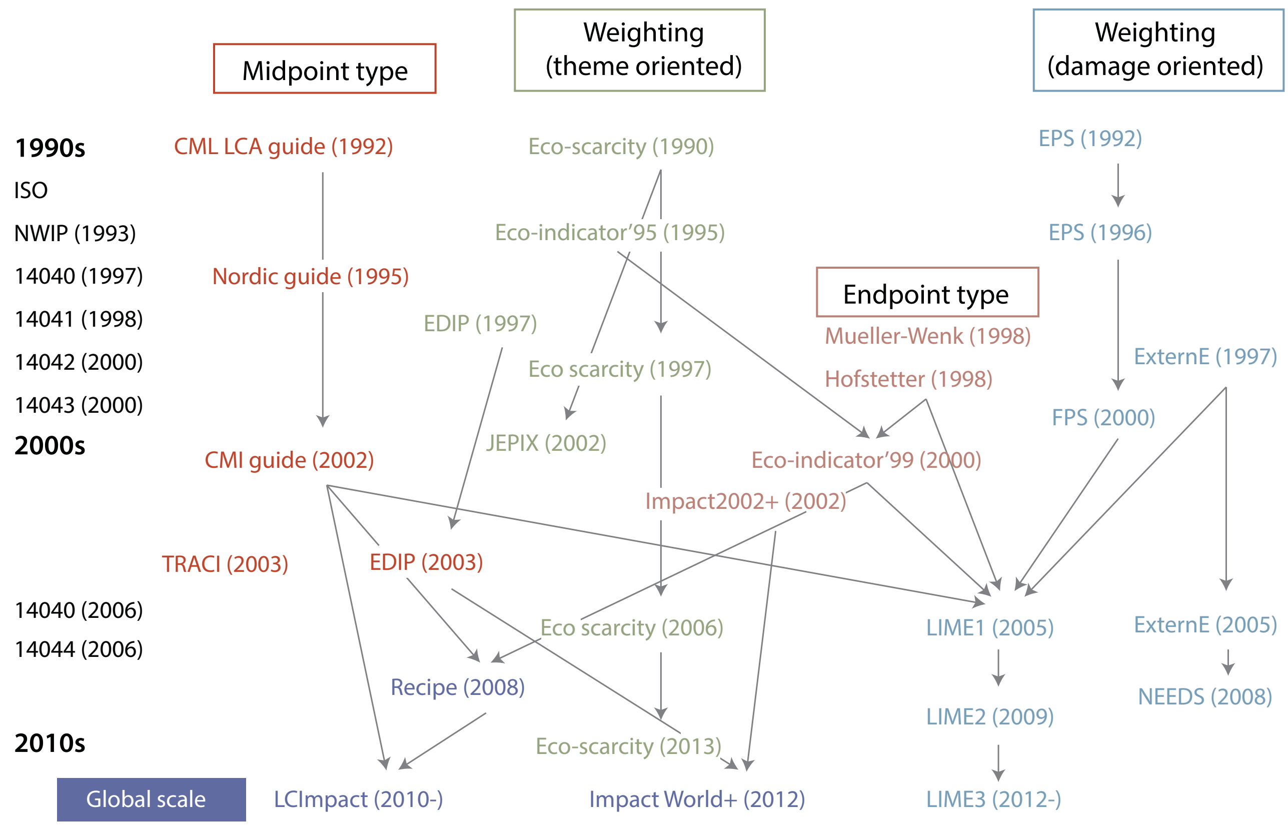

Figure 1.1: Evolution of Environmental Life Cycle Impact Assessment Methods (Itsubo 2012)

based on criteria such as distance to target or monetization (Figure 1.1); methods that were mostly developed for individual countries or continents.

A series of complementary initiatives for LCIA consensus finding have taken place since the early 1990s, providing recommendations and guidance for the development and use of LCIA methods. Following an initial workshop conceptualizing and framing LCIA approaches (Fava et al. 1993), two rounds of SETAC working groups led to category-specific recommendations for developing LCIA impact indicators (Udo de Haes et al. 2002), taking advantage of broader consensus efforts, such as those led by the Intergovernmental Panel on Climate Change for climate change issues. The LCIA program in phase I and phase II of the UNEP/SETAC Life Cycle Initiative developed a combined midpoint-endpoint framework (see Figure 2) relating various impact categories to damage categories, and provided further recommendations for multiple impact categories. The UNEP-SETAC toxicity model was then developed and endorsed to estimate ecotoxicity and human toxicity impacts in LCA (Rosenbaum et al. 2008). In parallel, more emphasis was given to better frame resource-related categories, especially for land use (Milà i Canals et al. 2007) and water use, with the launch of a water use LCA workgroup (Köhler 2007). Since the launch of phase I of the Initiative and the publication of its framework, progress has been made towards developing a worldwide applicable method, with spatially differentiated impact indicators, at midpoint (Hauschild et al. 2011) or endpoint levels (Bulle et al. 2016; Frischknecht & Büsser Knöpfel 2013; Huijbregts et al. 2014; Itsubo & Inaba 2010).

The ongoing developments in the application of LCA methods to product environmental footprint and to a wide range of products, call for not only providing recommendations to method developers, but also to provide recommended indicators that can then be used in such footprints within comprehensive LCIA approaches. With the globalization of economies there has also been a steadily growing need to create a worldwide consensus set of environmental impact category indicators embedded in a consistent, methodological framework. Such a set of indicators is expected to be used in environmental product information schemes, benchmarking in industry sectors, corporate reporting by companies, intergovernmental and national environmental policies, and common LCA work commissioned by governments and companies.

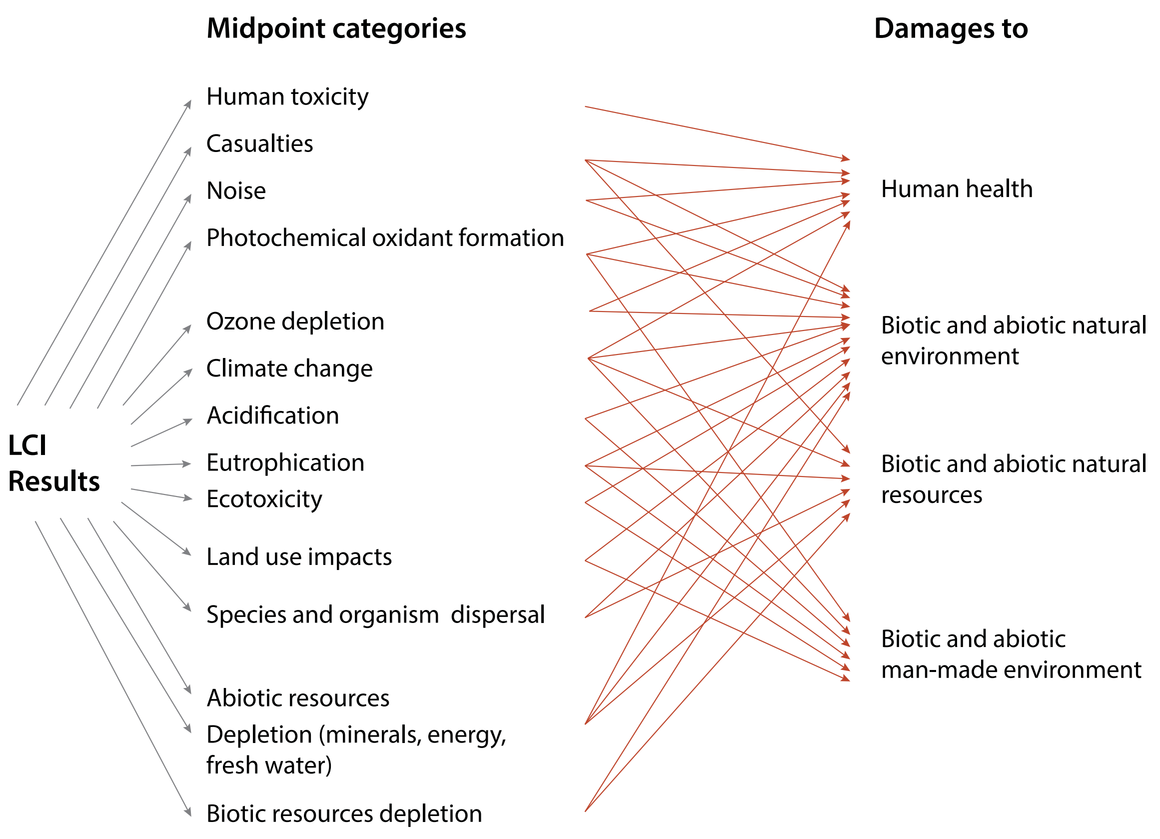

Figure 1.2: Life Cycle Impact Assessment Framework (Jolliet et al. 2004)

1.2 Objectives and working process

To answer these needs, Phase 3 of the UNEP/SETAC Life Cycle Initiative (2012-2017) launched a flagship project to provide global guidance and build consensus on environmental life cycle impact assessment indicators. Initial workshops in Yokohama in 2012 and Glasgow in 2013, as well as stakeholder consultations scoped this flagship project (Jolliet et al. 2014), focusing the effort in a first stage on a) impacts of climate change, b) fine particulate matter health impacts, c) water use, and d) land use, plus e) cross-cutting issues and f) LCA-based footprints.

For each of these impact categories, the main objective of the flagship is to (1) identify the scope of the work, (2) describe the impact pathway and review the potential indicators, (3) select the best-suited indicator or set of indicators based on well-defined criteria and develop the method to quantify them on sound scientific basis, (4) provide characterization factors with corresponding uncertainty and variability ranges, (5) apply the indicators to a common case study to illustrate its domain of applicability, (6) provide recommendations in term of indicators, status, and maturity of the recommended factors, applicability, link to inventory databases, roadmap for additional tests, and potential next steps.

To achieve these goals, task forces were set up involving more than 100 leading environmental and LCA scientists, organized in impact category specific task forces (TFs) and complemented by a cross-cutting issues TF. Multiple topical workshops and conferences were organized by each individual TF to first, scope the work and then, develop scientifically robust indicators suitable for a global consensus (Boulay et al. 2015; Cherubini et al. 2016; Curran et al. 2016; Fantke et al. 2015; Hodas et al. 2016; Levasseur et al. 2016; Teixeira et al. 2016). This was followed by two overarching workshops and stakeholder meetings in Basel 2014 and in Barcelona 2015 to address specific critical cross-cutting issues and collect feedback from multiple stakeholders.

Additionally, a LCA case study on the production and consumption of rice common to all TFs has been developed and published (Frischknecht et al. 2016). Three distinctly different scenarios of cooking rice have been defined and supported with life cycle inventory data. This LCA helps to test the impact category indicators that are being developed and/or selected in the harmonization process. It further helps to assess the practicality of the final, recommended impact category indicators.

This first part of the consensus-finding process ended with the present Pellston Workshop®, a one week workshop that took place 24–29 January 2016 in Valencia, Spain, where invited experts and stakeholders agreed on the recommended environmental indicators for each impact category.[1]

1.3 Quantifying life cycle based environmental impacts

LCIA is about the quantification of potential environmental impacts caused by the supply chain of products and services (product LCA), as well as by the activities of organizations including the upstream and downstream suppliers (organizational LCA, International Organization for Standardization (ISO) 2014; Martínez Blanco et al. 2015). LCIA methods, environmental impact category indicators, and environmental damage indicators are thus challenged by numerous and complex supply chains that span the globe and spread over several years, if not decades.

The model, methods, and indicators that would qualify for broader use in an LCA context must be flexible, robust, and able to cope with lack of geographically and temporally refined information.

At the same time it is acknowledged that indicators suited for LCA purposes are not always able to quantify real, empirically verifiable environmental impacts. Environmental impact category indicators report about potential environmental impacts (Fava et al. 1993; Heijungs et al. 1992a, b; International Organization for Standardization (ISO) 2000) and they are linked to a specific functional unit, be it a 100 km drive in a car fueled in Bangkok with bioethanol produced from Brazilian sugarcane, 1 cup of Costa Rican coffee enjoyed in Valencia that was roasted and packed in Switzerland, or using a smart phone manufactured in China with aluminium sourced from Australia. Nevertheless, some of the recommended models – in particular those used to quantify the effect of greenhouse gas emissions on global temperature, the one assessing the human health impacts related to primary particulate matter emissions, and the one

1 See the Foreword by SETAC for additional description of the history and structure of SETAC Pellston workshops.

assessing the loss of terrestrial species biodiversity caused by land use – have been successfully validated against trends in global or regional environmental impacts observed in the past.

The environmental impact category indicators recommended in this guidance are primarily suited for hot spot analyses in product and organizational LCA. Some of them are also suited for identifying hot spots in consumption-based assessments of the environmental impacts of nations (Frischknecht et al. 2015; Tukker et al. 2014) and intergovernmental organizations such as the European Union (JRC 2012). The indicators try to model complex cause-effect chains in general and disregard specific local aspects. Therefore, they are not (yet) fully suited for the identification of environmentally optimal agricultural management practices for a particular farm, a particular agricultural, or a forestial land with respect to terrestrial biodiversity protection. They are also not fully ready for the measurement of actual human health impacts of particulate matter emissions in a particular city district, nor in the prediction of human health effects of a severe drought period in a given year in Central Africa.

1.4 Guiding principles for LCIA indicator harmonization

The following global guiding principles were identified and applied in the LCIA indicator harmonization process:

- Environmental relevance ensures that the scope covered by the recommended indicator addresses environmentally important issues
- Completeness ensures that the recommended indicator covers a maximum achievable part of the corresponding environmental issue and has global coverage
- Scientific robustness, evidence, validity, and certainty ensure that the recommended indicator follows current knowledge and evidence rather than opinions, subjective or arbitrary choices, and normative assumptions
- Documentation, transparency, and reproducibility ensure that the scientific principles, models, and data supporting the recommended indicator are accessible to third parties and thus facilitate review and quality assurance
- Applicability ensures that the recommended approach can easily be implemented in LCA software, LCA databases, and corporate environmental management systems and supports the environmental assessment of complex supply chains, including a large variety of background processes
- Level of experience ensures that the recommended indicator has been applied in a number of sufficiently diverse LCA case studies and thus has proven its practicality
- Stakeholder acceptance ensures that the recommended indicator is applied in LCA-related work carried out or commissioned by industry, administration, and non-governmental organizations, and in communication with business and consumers

The harmonization work does not aim at providing a complete set of environmental life cycle impact assessment indicators. It is also not intended to create a new and comprehensive life cycle impact assessment method. The fact that this report includes guidance on indicators covering the four topical areas climate change, respiratory inorganics, water use related impacts, and land use related biodiversity impacts is not to be interpreted as an implicit expression of preference on these topics over others such as acidification, eutrophication, noise, or mineral resource depletion, nor as an implicit encouragement to use only one of the recommended environmental impact category indicators. When performing a product or organizational LCA it is highly recommended to use a broad set of environmental impact category indicators. This set should be tailored to its goal and scope and suited to address the variety of material environmental impacts to be expected from the activities of the organization and the supply chain of the product at issue, respectively.

The indicators recommended and the framework presented in this guidance document are primarily developed for damage-oriented environmental indicators and approaches. However, they do also apply to other conceptual approaches such as distance to target (see e.g., Frischknecht et al. 2013).

1.5 Link to life cycle inventory analysis

In the past, LCI and LCIA were often developed independently. Land use inventory flows were provided with first background databases in the early nineties without the accompanying impact category indicators to actually assess the environmental impacts related to land use. Meanwhile, more and more environmental impact category indicators are provided with a geographical granularity that requires more data collection efforts. These developments also challenge the step-by-step procedure described in ISO standard 14044:2006 for LCA, 1) collect unit process data, 2) compute the cumulative LCI results, 3) perform the impact assessment (International Organization for Standardization (ISO) 2006), as well as the computing structures of current LCA software. Such an approach fosters innovation in both domains (LCI and LCIA) and helps improve the reliability of LCA results and thus the usefulness of LCA in product stewardship and greener production and consumption.

Subsequently, special attention was given to the link between the environmental impact category indicators recommended in this guidance report and the current capabilities and constraints of current LCI databases. First, some of the participants have long-term LCI database experiences. Second, an LCA case study on the cultivation, processing, distribution, and cooking of white rice in three different scenarios was designed for that purpose (Frischknecht et al. 2016), initiated by the particulate matter task force chairs. In particular, the rice LCA case study serves the following purposes:

Rice cultivation causes methane emissions, which helps the global warming task force test their candidate and recommended indicators.

Rice cultivation requires irrigation (to a varying extent) and land use in different regions of the world, providing an excellent basis for testing candidate and recommended indicators of the water use and land use task forces.

Rice cooking may be practiced indoor with firewood causing potentially severe health effects. Furthermore, distribution and consumption of the rice happens in either rural or urban areas. The indoor and outdoor as well as urban and rural characterization factors developed and recommended in the particulate matter task force were linked to and tested on these different scenarios.

The supply chain is sufficiently complex to urge the experts to also provide default factors, applicable on situations with little or no geographic or temporal information.

Finally, the activities covered with the rice supply chains may cause further environmental impacts such as eutrophication (fertilizers applied in the rice fields), eco and human toxic effects (pesticides applied on the rice crops), and primary mineral resources (natural phosphorous extracted for fertilizer production). Therefore, the case study may be used again in the future when harmonizing further environmental impact category indicators.

Different approaches exist to adopt regional or geographic variability. The particulate matter and land use impacts task forces propose archetypes related to the characteristic of the location (urban vs. rural, outdoor vs. indoor) and related to the type of activity (e.g., annual crop cultivation), respectively. The water use task force uses geographically granular characterization factors. On the other hand, this topic was not of high priority in the climate change task force. However, all task forces acknowledged the need for generic characterization factors as they are often useful and practical in current LCA studies.

1.6 Context and procedure towards global guidance on LCIA indicators

This guidance document derives from a definition of the audience, the work process which culminated in the workshop, the level of consensus, and the concept that the principles are supportable without requiring absolute consensus among experts. The subsections of this topic address the target audience for the guidance, the status and role of the preparatory work, the criteria for recommendations, and the level of consensus.

1.6.1 Target audience

The main target audience of this guidance document are representatives in industry and governments using LCA in strategic planning, environmental management, product improvement, and in setting policies. This target group is particularly relevant when it comes to commissioning life cycle–based information on the environmental impacts of new products, policy measures, activities of a corporation, consumer information, business to business communication, etc. The guidance document allows them to ask for environmentally relevant and consolidated quantitative information related to the impacts of the emission of particulate matter, greenhouse gases, land use, and water use. Another important target audience of this guidance document are developers of LCIA methods interested in following the updated LCIA framework and or implementing consensus-based environmental indicators into their LCIA framework.

LCIA indicator developers in the field of climate change, particulate matter, water use, and land use are the third group of individuals and organizations who would benefit from the contents of this guidance document. They are inspired by the roadmaps specifically developed for each of the environmental topics addressed in this guidance document. These roadmaps highlight the main paths towards further improving the relevancy, reliability, and applicability of the indicators.

1.6.2 Status and role of preparatory work

This guidance document builds heavily on preparatory work performed by larger task force groups since the launch of the flagship project in 2013. These task forces discussed a relevant part of the topics addressed in this guidance document and prepared white papers, which formed the background material and the starting point for the Pellston Workshop® discussions. The preparatory work consisted of the following steps: 1) reach agreement on the exact scope of the environmental indicator for which it is developed. This included both the specification of the environmental impacts to be addressed and the LCA related questions for which the indicator is supposed to be suitable; 2) identify, describe, and evaluate existing approaches within and outside the LCA field; 3) agree on one or several candidate environmental indicators, which comply with the requirements and are likely to gain acceptance; 4) list the top priority questions and aspects to be discussed and agreed upon during the Pellston Workshop®. The Pellston Workshop® participants based their discussions on these white papers, as well as a large number of background reading documents. They are solely responsible for the recommendations put forward in this guidance document while at the same time acknowledge the invaluable preparatory work of task force members not physically present at the workshop. The achievements reached during the workshop are documented in this guidance document and will form the basis for a series of scientific papers authored by the topical task forces.

1.6.3 Criteria for recommendations and level of consensus

The recommendations presented in this guidance document are the result of consensus-finding processes based on objectively supportable evidence, with the aim to ensure consistency and practicality. However, they do not necessarily reflect unanimous agreement and, where necessary, minority views are also included in this guidance document, provided they are rationally grounded (i.e., based on facts, an underlying basis of argumentation in science, or demonstrated practical application) and are neither based on opinion nor on commercial interests. These minority views are not given the prominence of more highly recommended approaches (Sonnemann & Vigon 2011).

The body of experts assigns levels of support for a practice or indicator, according to the workshop process principles and rules. These levels are stated by consistently applying the terminology of "strongly recommended," "recommended," "interim recommended," and "suggested or advisable." Terminology such as "shall" or "should," normally associated with a standard-setting process, is avoided where possible. If such wording is used within a section of text, the reader is encouraged to consider such use as equivalent to use of the term recommendation with the corresponding level of support; for example, "shall" is equivalent to "strongly recommended." Interim recommendations are to be applied or used as default (rather than leaving out some inventory flows), while improved methods are being developed and can be used until better factors are made available. For some aspects, the experts may not have been able to formulate a clear recommendation. In these cases, either no supportable single recommendation is made or various alternatives are presented with no specific recommendation.

The criteria for classifying the level of support include, but are not limited to, the ones stated in Section 1.3.

While measures were taken to ensure consistent interpretation and application of the criteria listed above, it was in the hands of each task force to interpret the application of the criteria on the selected approaches, in all conscience.

1.7 Structure of this report

This report is structured along the topics discussed during the preparation and execution of the Pellston workshop. In Chapter 2 the slightly revised LCIA framework and a few cross-cutting issues are described with recommendations on how to address them. Chapters 3 to 6 cover the four topical areas: climate change, particulate matter, water use impacts, and land use impacts. These chapters contain sections documenting new findings, explaining the recommendations, addressing practicality issues, as well as specifying suggested and recommended future developments. Finally, Chapter 7 contains the synthesis and a description of the roadmap towards the development of even more complete and sophisticated LCIA indicators.

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2. LCIA framework and modelling guidance [TF 1 Crosscutting issues]

Francesca Verones, Andrew D. Henderson, Alexis Laurent, Brad Ridoutt, Cassia Ugaya, Stefanie Hellweg

2.1 Scope and objectives

It is our goal to make recommendations for good practice in LCIA modeling, and to ensure that new developments and findings can be integrated into LCIA in a way that makes environmental impact category indicators compatible. In addition, transparent reporting of all impact categories is a key concern.

This integration should occur both within areas of protection (AoPs) and across all categories. The cross-cutting issues task force has worked to identify areas that are in need of harmonization and to come up with recommendations. Whenever possible, we have aimed to distinguish between recommendations for the near-term and recommendations for a longer-term, which should help to steer further research into the desired direction. Albeit many recommendations are directly targeted towards impact assessment developers, recommendations may be nevertheless useful for practitioners too. Where relevant we have explicitly distinguished between recommendations for practitioners and those for method developers. Furthermore, recommendations made should in no way stifle further work and development on cross-cutting issues.

In order to strive towards consistency among impact categories, the task force has been organized into a number of sub-tasks on two different levels. The first level concerns cross-cutting issues that refer to all impact categories within one AoP, such as vulnerability inclusion for damage to biodiversity are only relevant within one specific AoP, in this example ecosystem quality; the second level concerns cross-cutting issues that concern all impact categories and areas of protection, such as transparent reporting and the overall impact assessment framework that are of utmost importance to all impact categories.

The issues addressed cover a wide range of topics. The overall LCIA framework will be presented first. Cross-cutting issues for impact categories within one specific AoP (e.g., human health, ecosystem quality, natural resources, ecosystem services, or socio-economic assets, see Table 2.1), dealing with for example endpoint metrics in the AoPs follow. Subsequent sections cover cross-cutting issues across AoPs, such as reference states, spatial differentiation, uncertainties, as well as normalization and weighting. One very important and overarching topic is transparent reporting. We strongly recommend to increase the transparency in reporting, both in documentations for impact assessment methods and reports of LCA case studies. Therefore, reporting, addressed in sub-chapter 2.5.2, is a recurring theme throughout the chapter and is valid for both method documentation and LCA applications.

2.2 Overall LCIA framework

The overall framework of life cycle impact assessment recommended by the UNEP/SETAC Life Cycle Initiative was initially defined by Jolliet et al. (2004). In the spirit of the Pellston workshop's exchange of ideas, and reflecting the diversity of task force, not all suggestions received unanimous support. This report communicates the decisions, recommendations, and directions of discussions from the workshop. As a minor update to this framework, we now distinguish between three different kinds of values (Table 2.1):

- Intrinsically valued systems, indicating a system, organism, place, etc., has a value by virtue of its existence. The assessment of ecosystem quality as well as human health impacts fall within this value type.
- Instrumentally valued systems, which have a clear utility to humans, namely natural resources, ecosystems services, and socio-economic assets.
- Culturally valued systems which have value to humans by virtue of artistic, aesthetic, recreational, spiritual, etc., qualities. These have so far rarely been assessed in LCA, but could be included in the future.

The same environmental intervention (elementary flow) may have ramifications in several of these categories. For example, workers' exposure to chemicals may lead to health impacts of the workers (damage category human health) and at the same time increase sick days and reduce the working time with economic implications (damage category socio-economic assets). We want to stress that natural resources and ecosystem services (Table 2.1) correspond to different values and are assessed in a different way. The reason for grouping them together in Table 2.1 is that they both have an instrumental value for humans and are both based in the natural environment.

The distinction between the biotic and abiotic environment within natural resources is no longer made. With the introduction of ecosystem services as a potential damage category, biotic resources would be shifted there, while natural resources will in general encompass parts of the abiotic environment.

In comparison to the previous framework by Jolliet et al. (2004), midpoints are no longer mandatory for each impact pathway and they do not need to be an intermediate result on the cause-effect chain and linked to an endpoint. Indeed, some impact categories do not have a natural midpoint along the cause-effect chain at which to create an intermediate indicator, as is for example the case for water or land use.

However, for reasons of transparency it remains important to model each impact category separately (either via midpoint indicators to the damage categories, directly to the damage categories, or with scarcity-related indicators, see also the chapter on water use). Figure 2.1 shows the new framework. Departing from the life cycle inventory analysis (left column) the various impacts of emissions and resources are assessed. The impact assessment can:

- either directly provide damage-based indicator results within the respective impact category (2nd column in Figure 2.1), directly feeding into the damage category (3rd column),

Table 2.1: Overview of values and damage categories.

Columns show a broad classification of values. Rows show the link to human systems (first row) and to the natural environment (second row).

Intrinsic	Instrumental	Cultural
Human health	Socio-economic assets	Cultural heritage
(morbidity & mortality)	(Man-made environment such as built infrastructure, cash crops, etc.)	(buildings, historic monuments, artwork, etc.)
Ecosystem quality	Natural resources Ecosystem services	Natural heritage
(e.g. biodiversity loss in terms of species richness & vulnerability)	(e.g. mineral primary resources, ecosystem services)	(e.g. flora, fauna, geological elements)

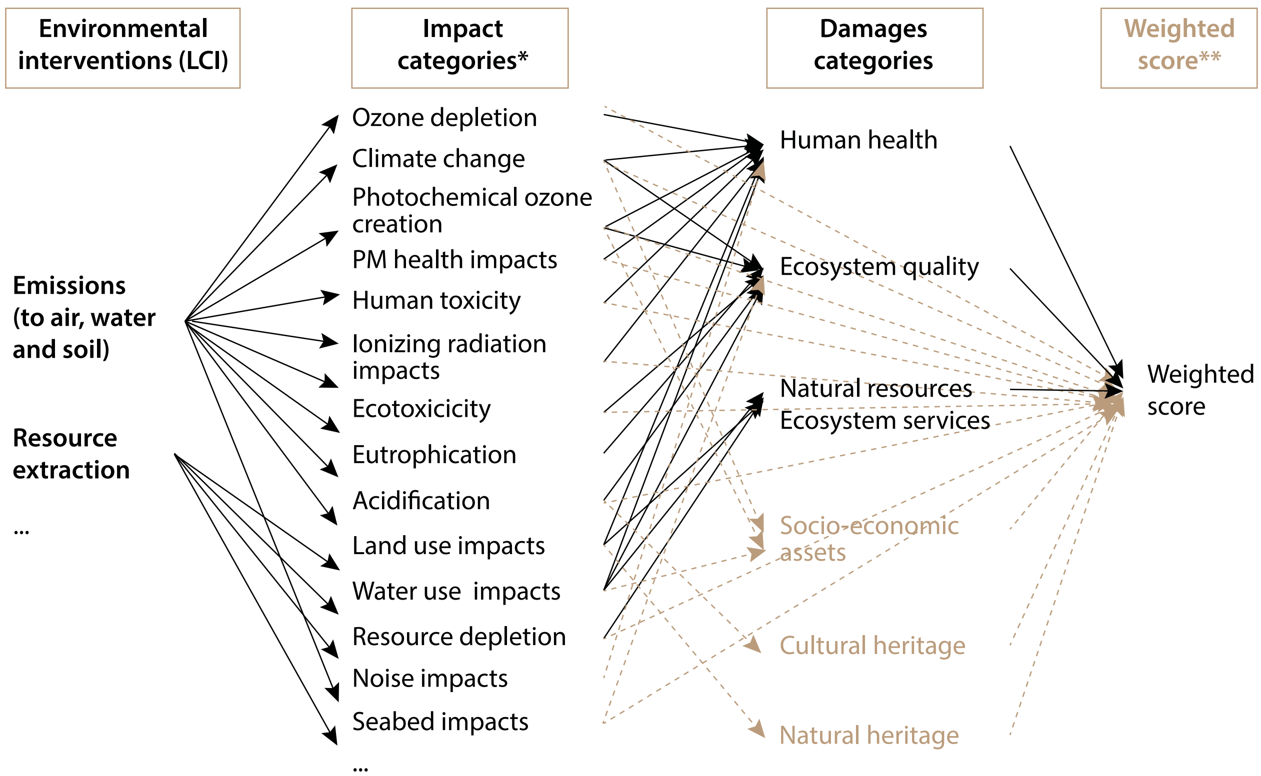

Figure 2.1: Updated structure of the LCIA framework.

*The list of impact categories is indicative rather than exhaustive and subject to change due to future developments. Be aware that all of the categories represent impacts. "Land use impacts" includes both land occupation and land transformation impacts.
**Weighting is an optional step in impact assessment which can be used to facilitate interpretation. Weighting may also utilize normalization.

- or first a pre-step is done (e.g., using ozone depletion potentials to derive an impact indicator for stratospheric ozone depletion – 2nd column in Figure 2.1) before going to the damage level (e.g., human health impacts from increased solar radiation caused by ozone depletion - 3rd column differentiated by impact category) eventually feeding then into an aggregated damage score (also 3rd column) (not explicitly shown in Figure 2.1),
- or an impact indicator is defined and not connected to any damage indicator (stopping at the 2nd column in Figure 2.1, see for example indicated exemplarily for noise and seabed damage).

Modeling up to the damage categories always has to be based on natural scientific principles. Therefore, impact and damage categories may both be used for comparative assertions, as defined in the ISO standards. Weighting may be performed either among impact indicators (2nd column) or between damage indicators (3rd column), to derive an aggregated impact score (4th column), but not mixing the two. Some weighting methods require previous normalization.

These changes in the overall framework as compared to Jolliet et al. (2004) reflect recent developments in LCIA, where for some environmental impacts no obvious midpoints exist, e.g., for ecotoxic impacts, while for others simplified indicators were defined that do not necessarily correlate with damage categories (endpoints), e.g., the AWARE method assessing the water scarcity caused by the consumptive water use. While some members of the task force felt that it would be desirable to always model impacts up to the damage categories (endpoint level), others did not agree, allowing also for other indicators to be assessed, e.g., at midpoint level.

2.3 Damage category specific recommendations

2.3.1 Cross-cutting issues human health

Introduction

Human Health is an important area of protection (AoP) in life cycle impact assessment (LCIA). A variety of impact categories contribute to this AoP including climate change, stratospheric ozone depletion, photochemical ozone formation, health impacts caused by respiratory inorganics ($PM_{2.5}$), human toxicity and water use impacts. This sub-chapter looks into the status of metrics used for Human Health with the goal of ensuring consistency across impact categories and to provide global guidance of how to assess impact categories within this AoP.

Recommendations

It is recommended that method developers:

- use the metric Disability-Adjusted Life Years (DALYs) at endpoint, as currently done in most LCIA methods. Human health impacts are appropriately defined at the population level, i.e., not in relation to individuals or susceptible sub-populations.
- use the most recent severity weights available from the WHO Global Burden of Disease (GBD). In the latest GBD 2010 (Lim et al. 2013, Salomon et al. 2013, Vos et al. 2013, Wang et al. 2013), neither age weighting nor discounting is considered in the calculation of the DALYs. As a starting point, the calculation of the DALYs should follow the GBD 2010 or 2013 (Forouzanfar et al. 2015) approach and not include age weighting nor discounting (average population considered; see above point).
- report separately and explicitly death, years of life lost (YLL) and years lost due to disability (YLD), disability weighting and severity factors used for scenarios of every disease separately, in addition to aggregated DALYs.

2.3.2 Cross-cutting issues ecosystem quality

Introduction

Ecosystem quality is an area of protection dealing with terrestrial, freshwater, and marine ecosystems and biodiversity, focusing on the intrinsic value of ecosystems. Impacts from land or water use, eutrophication, acidification or toxic effects are impacting these different ecosystems. Currently, the majority of operational methods addressing ecosystem quality are related to species disappearance due to data availability. Due to data availability and the intrinsic character of this area of protection, the recommended metric for this AoP is biodiversity loss.

In the last years, substantial advancements were made in LCIA in terms of impact pathways covered and complexity of covered impacts. Therefore, the need for harmonization and comparability across impact categories is becoming an increasingly important topic.

Cross-cutting issues that are relevant for this AoP encompass, among other issues, damage units and the issue of vulnerability.

Recommendations

Given the current prevalence of biodiversity-based impact assessment methods, it is recommended that the unit at the level of damage categories should be "potentially disappeared fraction of species" (PDF). Method developers are free to propose and use other units in their respective methods. However, it is strongly recommended that any method addressing biodiversity uses units that are convertible to PDF and that method developers describe this conversion and report the factor needed for transforming alternate units into PDF. Negative PDF-values are conceivable and would then represent a benefit (increase) of species richness (but see also section 2.5.3).

We recommend that CFs at different levels of coverage be developed:

- Global characterization factors, to reflect global, and hence irreversible, extinction of species. This reflects the global interest for preserving species and moving towards reducing irreversible biodiversity loss.
- Regional characterization factors, to reflect a loss of species at regional scales. This recommendation recognizes that the existence of a species at global level does not fully protect the intrinsic value of that species across ecosystems. Regional factors may help to ensure that regional ecosystems can retain their functions. The definition of the scale "regional" depends on the impact category and should reflect the nature of the impact, such as choosing ecologically homogenous regions for land use or (sub-)watersheds for ecosystem impacts, or even differentiating between lakes and rivers (for instance with respect to eco-toxic and eutrophying impacts).

It is strongly recommended to report explicitly at which scale the CF in question is developed, e.g., by using subscripts for each indicator and unit. CFs developed for different spatial scales cover different impacts (e.g., in terms of reversibility) and can therefore not be summed and aggregated without harmonizing them first. In order to aggregate between different scales, weighting procedures are needed.

We suggest method developers to report characterization factors in a disaggregated way, i.e., separately for different ecosystems types (aquatic, marine and terrestrial) and taxa, if applicable. In order to be able to sum taxa and different ecosystem types, weighting is needed.

We recommend to include a vulnerability term for impacts on species richness and possibly ecosystems, to reflect that there are species and ecosystems that are more at risk due to specific interventions than others. For example, in the case of species loss, not only species richness matters, but also endemism, which can be captured with a vulnerability indicator. Vulnerability is understood here as a broad term encompassing concepts such as endemism, rarity, resilience and recoverability of e.g., species or ecosystems.

Future development

Research is needed for developing more sophisticated harmonization procedures to aggregate impacts across spatial scales and across different taxonomic groups. The latter require weighting because species-rich taxa tend to dominate the impact assessment, even though they may not be the most vulnerable ones. It is recommended to investigate different options for how such a weighting can be performed, including but not limited to indications about species richness, and species vulnerability per taxonomic group.

We strongly recommend to LCIA researchers to explore how vulnerability can be included in ecosystem quality impact assessments. It is suggested to provide vulnerability data on ecosystem level and make sure it is consistently used throughout impact categories. However, due to the novelty of the concept in LCIA, no specific recommendation is given at this time.

2.3.3 Cross-cutting issues natural resources and ecosystem services

Introduction

Natural resources are material and non-material assets occurring in nature that are at some point in time deemed useful for humans. Natural resources include minerals/metals, fossil fuels, renewable energy sources, water, land/soil, and biotic resources such as wild flora and fauna in term of their instrumental value for humans.

Most existing LCIA methods have addressed abiotic natural resources (minerals and metals, fossil resources, water, land). Methods are rather diverse and there is no common agreement yet on how to model damages on natural resources. Different method types include methods aggregating resource consumption based on increased future effort/cost methods (e.g., surplus energy or cost), distance to target methods, reduced quality of natural asset methods or advanced accounting methods (e.g., exergy demand) (Sonderegger et al. internal task force report).

Recommendations

It is recommended that method developers also address the instrumental value of natural resources when developing impact indicators and characterization factors (Figure 2.1 and Table 2.1). Method developers are recommended to consider the different nature of resources, i.e., stocks (resources with a finite amount), funds (renewable, but overuse is possible) and flows (highly renewable and non-exhaustible).

The identification and further modeling of a general environmental mechanism, applicable to all resources, remains an outlook to undertake.

Ecosystem services are instrumental values of ecosystems and therefore impacts on ecosystem services are different from impacts on ecosystem quality, which has intrinsic value (see also sub-chapter on framework). Methods for quantifying and assessing ecosystem services (as well as damages to them) exist mostly outside of LCA; therefore, we encourage further research on how these existing methods can be adapted and incorporated into LCIA.

2.4 Spatio-temporal and modeling guidance

We assume that method developers will always make use of the best possible, feasible model available for constructing impact pathways. We also advise method developers, if possible, to adapt and update their models as improved modeling options become available.Method developers should consider the challenges of data availability to support their models.

2.4.1 Spatial differentiation

Introduction

All impact categories show spatial variation. Efforts to capture this variation range from approaches in the 1990s (e.g., acidification, (Potting et al. 1998)) to current regionalized impact assessment methods for a range of impact categories, such as land use (Brandão et al. 2012, Chaudhary et al. 2015, Frischknecht et al. 2013), water use (Boulay et al. 2011, Motoshita et al. 2011, Pfister et al. 2009, Verones et al. 2013), freshwater eutrophication (Azevedo et al. 2013, Helmes et al. 2012) or noise (Cucurachi et al. 2012). Spatial differentiation may help increase the accuracy of LCA results (Mutel et al. 2009). Relevant native spatial scales (see glossary) may vary between impact categories (e.g., air grid cells, ecoregions, or higher resolution hydrological data).

In impact categories for which spatially explicit models are created, information on modelled spatial scales should be published to facilitate the implementation of impact assessment methods, e.g., by linking with inventory and software, data sharing, and analysis by others. Therefore, it is important to harmonize the way in which spatially differentiated impact and damage indicators are published. This section aims at giving initial recommendations towards this end. Primarily, transparent and comprehensive documentation is strongly recommended; we provide specific recommendations beyond those in the transparent reporting subchapter. This documentation should specify data choices, model assumptions, discussion of chosen spatial scales for input parameters and for the final native resolution, procedures for aggregation to other spatial scales and procedures for uncertainty and variability estimation. Examples for describing all modeling steps should be provided in the documentation.

Scale choice

It is strongly recommended that method developers report the basis for their choice of spatial scale, even if they have chosen site-generic modeling (see glossary). The chosen spatial scale must reflect the nature of the impact. Ideally, the spatial scale of a model reflects a balance between the system being modelled (e.g., urban air and rural land use would likely require different spatial scales) and data availability. The various inputs to a model will usually be available at different spatial scales; the modeller should clearly document which parameters in their LCIA model and input data sets are regionalized, and at what spatial scale. It is recommended to use this information to explain how the overall spatial scale of the model was chosen. It is recommended to include comments about whether a different spatial scale would have been preferred, or if data availability limited choices of resolution. It is recommended to avoid using lower resolution data in high resolution models.

Maps and spatial data

To facilitate sharing their work with others, it is strongly recommended that method developers of spatially differentiated impact categories generate maps of characterization factors at the native scale. These maps and their underlying data should be:

1. in a format standardized by the Open Geospatial Consortium (OGC 2016), such as Geopackage for vector and raster files or GeoTIFF for raster files
2. have well-defined coordinate reference systems appropriate to the area of study (often global),
3. specify "nodata" values with a clearly identifiable value. The "nodata" value should be a value that does not exist elsewhere in the dataset, and should be clearly documented.

It is also recommended to make maps available for users, e.g., by including them in the supporting information of a journal publication. Characterization factors should additionally be published using existing impact assessment data formats to facilitate use in current LCA software systems.

Aggregation

To facilitate use of their work by others, it is strongly recommended that method developers also aggregate characterization factors, at the country, continental, and global (as appropriate) scales, clearly documenting how such aggregated factors were calculated. If relevant and differing from the native scales, aggregation can in addition also take place on other scales (e.g., biomes or watersheds). The following points are recommended:

- Aggregated values should be weighted arithmetic means. It is recommended to choose the weighting basis appropriate to the impact category and/or emission source/inventory intervention. Consumption-based or emission-based weighting is recommended (such as spatially differentiated total water use for aggregation of water use related impact assessments). It is recommended to clearly report the weighing approach and data used.
- Aggregated values should be reported in standard LCIA formats (see above).
- Spatial variability of factors needs to be reported (see below).

Archetypes

While country and continental may be useful aggregation scales for interim linking to inventory data, depending on the characteristics of the system being studied, archetypes may be a useful approach for aggregation. For example, indoor and outdoor, urban and rural, low and high-stack emissions provide meaningful distinctions for particulate matter (Humbert et al. 2011) and is recommended by Fantke et al. (2014) as an essential approach that is able to capture the resolution essential for making reliable intake fraction estimates for emissions of particulate matter and precursor substances.

Analysis: Uncertainty and Variability in spatial differentiation

To facilitate review and use of their work by others it is recommended that method developers provide an analysis of the variability and uncertainty of their characterization factors.

It is recommended that method developers report uncertainties with characterization factors. We recommend that contributors to uncertainty include those components identified in the uncertainty section (section 2.6). It is suggested that uncertainty be reported quantitatively. At a minimum, uncertainty is to be reported qualitatively.

It is strongly recommended that method developers report spatial variability and uncertainty in both native CFs and in aggregated CFs. It is expected that the variability reflected at the higher resolution becomes a source of uncertainty when aggregating at lower resolution. Variability at the native resolution is recommended to include, at a minimum, domain-wide median, mean, and the 95 % confidence intervals. It is recommended to report the same distribution information for all aggregated values (e.g., country, continent).

Future developments

Further research relevant for spatial differentiation include the following:

- Data formats for regionalized LCIA methods should be developed. These data formats should include multiple sources of uncertainty and variability of characterization factors and input parameters, documentation and discussion of chosen spatial scales
- Procedures for aggregation to other spatial scales.
- Database developers should prioritize the development of regionalized inventories in order to take advantage of spatial characterization factors. The selection of inventories to be regionalized should be based on systematic analysis of the existing database, to identify those that benefit most from regionalization
- In order to take advantage of regionalized inventory, LCA software should support regionalized LCA calculations and the data formats for regionalized LCIA methods. Moreover, LCA software should allow reporting of uncertainties in the CF at the different scales.

2.4.2 Time frames

Impact factors should consider the time frame during which impacts will occur.

In this regard, method developers are recommended to:

- separate modelled impacts into those occurring within 100 years and those that have a longer time horizon, e.g., occurring after 100 years. The use of the term "short-term" is discouraged for the former category, because of different perceptions of what short-term implies.
- when possible and relevant, use additive metrics to capture impacts within 100 years and those occurring after 100 years. When not possible, two separate indicators are recommended to be used, and cumulative impacts are recommended to be reported separately for (i) the first 100 years and (ii) the long-term impacts.
- report the separated metrics using subscripts, in particular when additive metrics are used.

2.4.3 Reference states and marginal versus average approaches

A reference state is a baseline used as a starting point against which we can quantitatively compare another situation. A reference state can be, for example, a (hypothetical) situation representing conditions in the absence of human intervention, an anticipated or desirable target situation or the current situation. A reference state refers to both a time period and space.

Currently, different impact categories often use different reference states. A preliminary study showed the lack of explicit information of the reference state used in several existing LCIA methods. As the selection of a reference state is a value choice that affects the outcome of specific values of CFs, method developers are recommended to document reference states explicitly and transparently. The rationale for the choice of the reference state is recommended to be stated according to the following three criteria: type, flexibility, as well as selection rationales and constraints.

In the criterion "type" the reference state is characterized: This can be, for example, a (hypothetical) situation representing conditions in the absence of human intervention, an anticipated or desirable target situation (e.g., political goal or a natural goal, e.g., 50% of ecosystem carrying capacity), or the current situation (which may be beyond the carrying capacity of the globe). The time period and spatial delineations are also to be included within this criterion.

The criterion "flexibility" measures whether the reference states are fixed (e.g., time → year 2000), sliding (e.g., time → current state or 20 years before assessment), definable (e.g., time → before industrial revolution), or individual (i.e., defined on a case-by-case basis).

The category "selection rationales and constraints" addresses if the chosen reference states were due to pragmatic reasons (e.g., data availability) or normative reasons (e.g., desirability).

Table 2.2 presents examples of reference states for the four impacts categories addressed in the present report.

One can notice that there are differences among the reference states described in Table 2.2. Whenever impact category indicator results are aggregated, different choices of each reference state (current, target,…) can influence damage category indicator results differently. Therefore, it would be desirable that the reference states are consistent.

Whenever impact categories category indicator results are aggregated, different choices of each reference state (current, target,…) can influence damage categories category indicator results differently. Therefore, it would be desirable that the reference states are consistent.

The selection of reference states influences the outcomes of CFs, resulting in different incentives or strategic recommendations. For example, consider that the reference state is defined as the current status. If the background concentration of particulate matter in a city is already high, a marginal increase might lead to only minor additional human health

Table 2.2: Examples of reference states for the four impact categories of the Pellston workshop according to the suggested criteria

	Climate change	Water		Land Use	PM2,5
		Aware	HH		
Type category	Current situation (2015)	Current situation of water consumption and water availability, monthly data	Current situation, FF: monthly, watershed EF: annual, country	Natural undisturbed habitat in same region (Chaudhary et al. 2015, de Baan et al. 2013)	Reflects the current state of the global environment for marginal or the background PM concentration (5.8 µg/m^3), the DALY referring to the longest life expectancy (Japanese woman) Time: time-integrated over at least one year, health effects integrated over lifetime Region: global average (Tier 1) or city level (Tier 3)
Flexibility	Fixed (2015)	Fixed	Fixed	Individual (paired studies)	Fixed at all scales
Normativity	Pragmatic	Pragmatic: "current" is reflecting long-term availability 1960-2010; 2010 water consumption for human demand; 30-60 % of natural water flow for ecosystem demand	Pragmatic: "current" is reflecting long-term availability 1960-2010 and 2010 for water consumption. For DALY per case:~2013 For cases per kal deficit: 2012-2014	Normative: representative of measured species in natural state	Pragmatic: 2011 to assume robust data

effects. This could lead to a conclusion that the additional pollution in that region is not relevant and no incentive is given to reduce the emissions and thus the impacts (see red line in Figure 2.2). In such a case it may be more appropriate to choose a future target value or the average response as reference state, to incentivise emission reductions or to reflect that the decision takes place in the context of much larger changes in background concentrations (see blue line in Figure 2.2). As a result, the reference state should be defined according to the purpose (large scale or long-term study involving potential reduction to a "sustainable" level versus small-scale study examining what is the short-term impact of a small additional increase). Additionally, each new method needs to describe the implications of this choice.

Marginal/average/linear approach

For some impact categories a marginal approach is followed in LCIA, departing e.g., from the current state (e.g., the slope of an exposure-response curve at a given background concentration) (red, dotted line in Figure 2.2). For other impacts, an average approach is assumed (Huijbregts et al. 2011) (blue, dashed line in Figure 2.2), e.g., in land use impact assessment the difference between the biodiversity of a potential natural state versus land use scenarios may be assessed. Finally, in some cases, a linear relationship (going through zero) is assumed to simplify the assessment, e.g., for toxic impacts (Rosenbaum et al. 2008).

It is recommended that method developers provide two sets of characterization factors, in particular, regarding emission related impact indicators:

1. A set of marginal characterization factors, which ideally takes the current situation as the working point (e.g., the current background concentration of toxic substances in air, water and soil to quantify toxic impacts). These marginal characterization factors are most appropriately applied in LCA studies where relatively small changes in overall emissions re expected to occur (i.e., the decision taken based on the LCA is unlikely to affect background concentrations or short-term perspective for which important changes are unlikely to occur).
2. A set of average characterization factors, which select a situation without human intervention as the reference state. Average factors may e.g., be relevant in the case of decisions leading to larger changes in the economy or taking place in the context of longer time frame for which larger changes in background concentrations are expected.

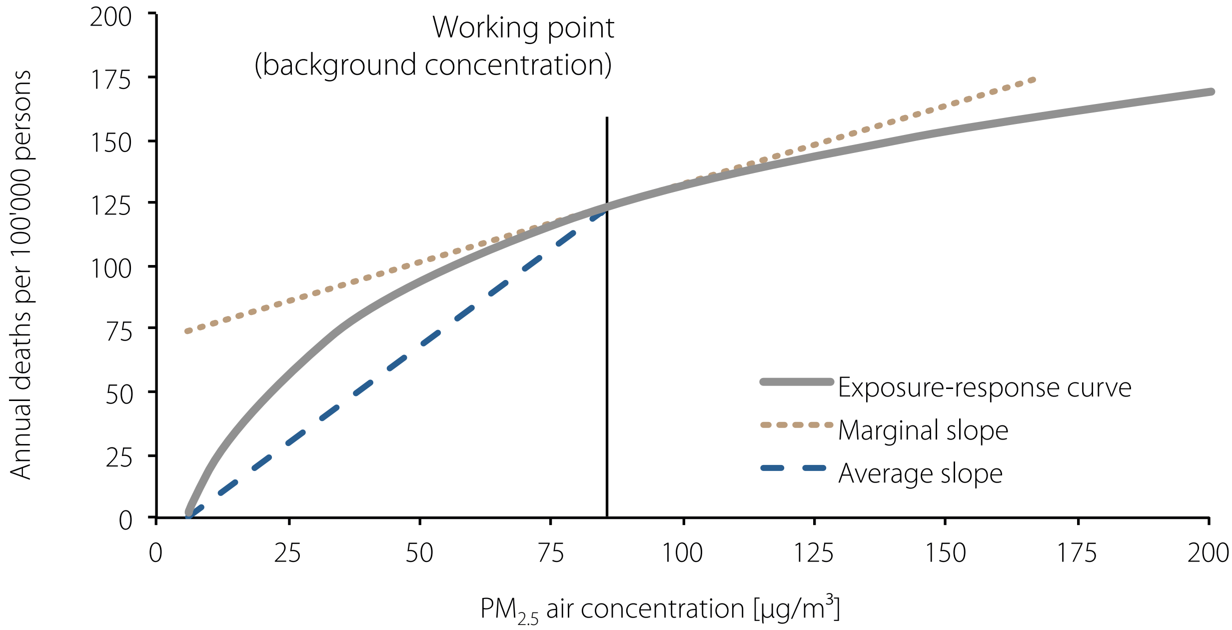

Figure 2.2: Illustration of applying the exposure-response curve for calculating health impacts from exposure to PM2.5

Red dotted line shows an approach for the calculation of marginal characterization factors related to the background concentration at the working point, while blue dashed line shows an approach for calculating average characterization factors as average between the background concentration at the working point and the theoretical minimum-risk concentration. The working point used as example is the actual background concentration in (Apte et al. 2015).

2.5 Uncertainty and transparent reporting

2.5.1 Uncertainties

Introduction

Currently, most life cycle impact assessment (LCIA) results lack any quantitative uncertainty information. However, all of the methods do contain multiple uncertainties. Only once uncertainties are reported alongside with characterization results will a proper and more accurate interpretation be facilitated. This is of utmost importance as basis for sound decisions. We strongly recommend that an informed decision is based on numeric characterization results and consideration of uncertainty. This also helps pinpointing uncertainty hot-spots, which defines the research agenda for further improving LCIA methods and tools across impact categories.

Moreover, most effort in terms of uncertainty has so far been made regarding life cycle inventories (LCI) and much less is available for LCIA. Types of uncertainty that are covered are different between different impact categories. There are different levels of correlation (Technosphere, ecosphere, LCI, see Pfister and Scherer (2015)).

The main goal of this subchapter is to build guidance for a consistent uncertainty assessment framework that can be applied across impact categories in LCIA.

Recommendations

It is strongly recommended to make all uncertainties explicit by reporting them at least in a qualitative way and by identifying and highlighting the most relevant contributors to uncertainties. The relevant categories of uncertainties that should at least be included in the reporting are:

- Input data uncertainty
  - » Parameter uncertainty
  - » Uncertainty of external model data
  - » Expert guesses
- Model Uncertainty:
  - » Model selection
  - » System boundaries (e.g., cut-offs)
  - » Assumptions
  - » Model simplifications
- Variability:
  - » Any aggregation of results over time or space (or other relevant aggregation)
  - » Aggregation of substances, types of substances for a specific use
- Value choices:
  - » Geographical scope (if any)
  - » Time horizon / discounting over time
  - » Any weighting factors or thresholds (e.g., weighting factors for spatial aggregation)
  - » Inclusion/Exclusion of positive effects / adaptation / resilience and others
  - » Reference state assumptions for current and future impacts
  - » Level of knowledge / certainty of effects (includes some of the cultural perspective aspects)
- Scenario Uncertainty:
  - » Missing information
  - » Other relevant information related to the scenario

Further, it is recommended to provide for the above quantitative uncertainty estimates, wherever possible. Moreover, for the case that important uncertainties may not have been quantified, it is recommended to explicitly report on these uncertainties in a qualitative way. If archetypes are used, it should be assessed how to consider uncertainty due to variability in characterization factors as function of level of archetypal aggregation as outlined in Chapter 7 for PM-related impacts (see Figure 4.2).

Future development

Impact assessment methods that are able to quantitatively assess more types of uncertainty should not be penalized by raising the impression that these impact categories are more uncertain than others that do not report uncertainties. To this end, the introduction of a generic uncertainty factor should be investigated, including uncertainty linked to lack of environmental relevance. Once uncertainties can be quantified, the generic uncertainty factor (or a qualitative value based on a Pedigree matrix (Weidema et al. 1996) can be deduced. We realize that there are drawbacks associated with this procedure, which need to be carefully considered in future.

It is suggested to also look towards other sources for information on uncertainty. One such example could be the global burden of disease for particulate matter.

60 % of PM-related impacts are occurring indoors, thus methods that only include PM-impacts from outdoor emissions, may underestimate the world-wide health impacts by at least 60 %. However, while it may be relevant for the method, depending on the functional unit chosen this does not need to be true for every LCA study.

Further, a way in which yet unknown uncertainties can be dealt with should be explored.

Research is also needed to:

- identify which uncertainties can be quantified and which cannot,
- investigate how to address them (harmonised guidelines/requirements for characterising/reporting; consider correlated and uncorrelated uncertainties within and across impact categories)
- investigate the possibility to normalize uncertainty and be thus able to make them comparable
- investigate whether a "pedigree matrix" (Weidema et al. 1996) can be developed to characterise uncertainties in LCIA until better quantification can be done later
- Investigate uncertainty associated with the lack of environmental relevance and the level at which the indicator modeling reflects the impact pathways
- investigate the inclusion of expert judgements for evaluating uncertainties

Further, we strongly recommend software developers to evaluate possibilities for including options to handle LCIA uncertainties in their software.

2.5.2 Transparent reporting

Introduction

Transparent reporting is a key issue for the appropriate application of LCIA methods, and hence the credibility of LCIA. Therefore, the topic of transparent reporting applies to all impact categories and AoPs. In summary, we recommend the following for how and what needs to be reported. These recommendations are in part described in more detail in the following sections.

Recommendations

We strongly recommend that method developers:

- Document comprehensively and transparently the impact assessment models and resulting LCIA methods. It is strongly recommended that method developers report (i) the version number of the characterization factors set used, (ii) the included and excluded impacts, (iii) the impact pathways modelled, and (iv) the data sources, underlying assumptions and modeling choices used to cover these impact pathways. In the latter, method developers are recommended to document transparently the level of spatial and temporal differentiation and coverage for the different components of the impact pathways (e.g., fate, exposure, effects) and for the resulting characterization factors (see also Section 2.3), the reference states used (see Section 2.3) and the influence that the modeling choices may have on uncertainty (see Section 2.6).
- Clearly define all units used. All results, including intermediate calculations, should have identified units.
- Explicitly describe and justify modeling choices, and underlying assumptions. We encourage modelers to be as comprehensive as possible in this, including, but not limited to spatial and/or temporal coverage, used input data, parameters and models etc. that could affect uncertainty of the impact pathway.
- Document explicitly if and how linear and non-linear mechanisms within an impact pathway are addressed in the method and whether average or marginal approaches are used. It is advised that method developers document the implications of non-linear mechanisms, in particular the fact that marginal impacts in highly affected populations or highly stressed ecosystems may be significantly lower compared to marginal impacts in less affected populations or less stressed ecosystems – see further details in Section 2.2.
- Evaluate potential differences between alternative assessments to LCA (e.g., using emission database coupled with LCIA methods or use of epidemiological studies such as GBD2010) as "attempted validations" of the LCIA methods -see also Section 2.10. Feasibility and significance of such checks and the potential resulting discrepancies may vary across impact categories.
- Explicitly report reference states and their rationale, based on a set of criteria (detailed in section 2.3 on reference states).
- Report uncertainties qualitatively and quantitatively if possible (see section 2.6).
- Report transparently on variability in spatial

models, as well as variability added through aggregation (see section 2.5).

- Report the validation of models, or portions of models, if possible. For example, model predictions of individual exposure to PM can be scaled up and compared to epidemiological studies for PM exposure.

We recommend that in addition, practitioners:

- Report transparently which normalization and/or weighting approaches are used, and if relevant, how the practitioners have derived the factors (e.g., weighting factors for panel weighting).
- Report separately the characterized results, the normalized results and/or the weighted results whenever normalization and/or weighting are used.

As a summary of the recommendations given in section 2.3 and 2.4, we have created Table 2.3, summarizing the possible, recommended characteristics for method development for human health and ecosystem quality. The other damage categories require more consensus before such a list can be established. We do not recommend to develop one specific combination of factors, as this may differ from impact category to impact category.

2.5.3 Negative characterization factors

Introduction

In some impact or damage categories, characterization factors may be negative. For instance, SOx emissions may cause global cooling, leading to a negative characterization factor for climate change impacts (IPCC(2013), Chapter 8, Table 8.SM.18). On the other hand, SOx also has damages concerning, e.g., acidification. The negative factors may lead to erroneous conclusions, e.g., if only single impact categories are assessed, without addressing potential impacts in other categories.

Recommendations

Recommendations to software developers and/or practitioners:

- It is recommended that impact category indicator results from negative CFs should be reported separately, next to the overall impact score in the respective impact category (e.g., as a stacked bar).
- It is recommended to make clear that substances with negative characterization factors in one impact category may have impacts in other categories. In such cases, it is strongly recommended to include the latter impact categories in the study.
- Negative impacts may also arise from negative inventory flows. In such cases, we recommend to report the positive and negative results separately as well.

2.6 Normalization and weighting

Introduction

The ISO 14044 standard defines normalization as the "calculation of the magnitude of the impact indicator results relative to reference information" and weighting as the "conversion and possible aggregation of indicator results across impact categories using

Table 2.3: Overview of characteristics of damage categories that are important for method development choices and that should be reported transparently

For details, see the text in sections 2.3-2.5.

Characteristic	Human health	Ecosystem quality
Metric	DALY	PDF
Approach taken	Marginal/average	Marginal/average
Spatial scale	Chosen scale, aggregation at relevant scales (countries, continents,…)	Chosen scale, aggregation at relevant scales (countries, continents,…)
Temporal dimension (if applicable)	< 100 years >100 years	< 100 years >100 years
Reference state	Follow table 2.2	Follow table 2.2
others	Report YLL, YLD; disability weights, severity factors and DALYs	Distinguish between global CFs (irreversible extinction) and regional CFS (loss of functionality)

numerical factors based on value-choices" (ISO 2006). As part of the LCIA phase, normalization and weighting are both stated as optional steps (ISO 2006).

The purpose of normalization is to:

1. put results in perspective to facilitate interpretation and communication of the results, taking each impact category as stand-alone, and reflecting the magnitude of the impact results,
2. bring the results on a common unit as a preparation for further weighting (where prior normalization is required),
3. check the plausibility of the LCA results, i.e., are they in the right order of magnitude with regard to the object of assessment?

While normalization addresses the magnitude of the impact results, weighting of the impact results aims at reflecting the significance of the impacts with respect to each other and allowing aggregation of the impact results into a single score indicator, thus contributing to facilitate interpretation and communication of the results.

Existing approaches have been identified for both normalization and weighting (Pizzol et al. submitted)– for terms and explanations see glossary.

Recommendations to method developers

Recommendation for the development of normalization references

As part of further normalization-related research, method developers are recommended to:

- develop sets of per-capita global normalization references with (i) increased consistency (e.g., robust extrapolation techniques for gap-filling), (ii) increased completeness.
- use bottom-up approach for calculating normalization references (e.g., publicly available emission databases and LCIA methods) and use top-down approach for cross-checking (e.g., GBD (2010) for human health). Potential discrepancies can be fed back to method developers of the respective impact categories to perform a deeper analysis (incl. identification of causes and possible need for adjustments in LCIA).
- characterize and quantify uncertainties in external normalization references (see glossary) for all impact categories.

Recommendation for the development of weighting factors

As part of further research on weighting, method developers are recommended to:

- improve robustness, use of sensitivity analysis and the transparency of weighting approaches (incl. its limitations and uncertainties) and how the factors were derived. This includes quantifying the uncertainties of the derived weighting factors with respect to the assumptions and data used, providing clear and accessible description of the principles and defining a clear scoping of the application/applicability of the methods.

It is also suggested to:

- embark on a (social-science) expert-led process to establish guidelines for practitioners that need to elaborate weighting factors, in particular for panel-weighting methods.

The concept of planetary boundaries may be an interesting option for characterization, normalization and/or weighting in the future (as a distance-to-target approach). However, at this point in time, due to the immaturity of the integration of planetary boundaries or carrying capacities into LCIA, no recommendation was found acceptable on the matter.

Recommendations to practitioners

If normalization is applied in LCA case studies, practitioners are recommended to:

- use external normalization rather than internal normalization for interpretation of the results (when normalization is applied), see glossary for definitions. Internal normalization embeds important limitations when combined with generic weighting factors, e.g., potential change of the ranking of alternatives depending on inclusion or exclusion of alternatives and depending on the selected normalization reference. Internal normalization is however appropriate for illustrating and communicating impact results of comparative studies (it requires a minimum of two alternatives or scenarios).
    - » prioritize the use of external normalization references defined at global scale over continentally or sub-continentally defined normalization references when addressing systems that extend beyond the boundaries

of an individual country or region, which is the case with most LCA systems. Practitioners are strongly discouraged to mix normalization references with different geographic scopes (e.g., global and regional).

- check the consistency between the system boundaries – and the related LCI – of the analyzed system with the geographical and temporal scope of the normalization references, whenever production-based normalization references at regional scale (e.g., country, continent, region) are used. It is important to ensure that important environmental contributions from the system do not occur outside the geographical and temporal scope of the selected normalization references.
- apply normalization references for impact indicators defined at any point along the cause-effect chain and/or at damage indicator (category endpoint) level. Practitioners are strongly recommended not to sum up the normalized results across impact categories either within a same AoP, because aggregation of the impact indicator results within the damage category should first be done, or between different AoPs because prior weighting would then be required (unless equal weighting is assumed).
- perform sensitivity analysis by trying different weighting approaches and testing the validity of the results and conclusions.
  » interpret the normalized and weighted results with a clear understanding of their respective limitations and purposes. Because they only refer to the magnitude of the impacts in comparison to a normalization reference and do not account for their respective significance, normalized results do not allow for comparisons across impact categories at an intermediary (midpoint) level or across damage categories at the endpoint level – despite the temptation if plotted in a single graph as commonly done for communication purposes. Comparisons across impact categories should either be based within the same damage category on modeling up to the damage categories based on natural scientific principles on natural science or imply a value-based weighting step, which is recommended to be explicitly documented. Practitioners are also recommended to get an understanding and be aware of uncertainties associated with the different normalization and weighting approaches they use (based on documentation provided by method developers).

2.7 Relevance to discussed impact categories at the Pellston workshop and to the rice case study

This chapter has outlined several recommendations for LCIA method developers in relation to transparent reporting –see Section 2.3. These recommendations for transparent reporting apply to the LCIA methods described in this report as well as to those not addressed herein. Transparent reporting is necessary for practitioners to be able to apply characterization factors correctly and to support understanding of their limitations and eventually to ensure proper interpretation of the results (e.g., with consideration of impact pathway coverage, underlying uncertainties, model assumptions, etc.).

In addition, a set of global normalization references for the LCIA methods for water use, land use, climate change and particulate matter will be developed and used in the rice case study in compliance with the recommendations stated in Section 2.6.

2.8 Outlook

The cross-cutting issues task force has taken steps to help harmonize the development and associated documentation of LCIA methods as well as their applications in LCA case studies, with the ultimate goal to provide a more informed and consistent support to decision-makers. This harmonization effort has led to identifying several areas in which future research is needed, including (but not limited to):

- investigate and agree upon a framework for uncertainty assessment of LCIA methods
- an assessment of LCIA methods' uncertainties, both qualitatively and quantitatively
- coordinate with life cycle inventory and software developers to move towards systematic inclusion of impact uncertainty in LCA software
- including methods to assess damages to the instrumental values of resources and ecosystem services
- investigate and evaluate methods for assessing

ecosystem and/or species vulnerability in a way that takes resilience, rarity and recoverability into account

- representations of reversible and non-reversible impacts
- develop approaches to weight and aggregate CFs across different ecosystem scales and different taxa
- testing of methods that provide both marginal and average characterization factors through case study applications
- develop consistent sets of global normalization values

Furthermore, within the Life Cycle Initiative Global Guidance project, we recommend that future task force work to develop impact category indicators should be accompanied by cross-cutting discussions. Communication in this venue can thus identify inter-category differences and challenges early on in this development and facilitate their resolution.

2.9 Acknowledgments

The authors of this chapter would like to thank the members of the cross-cutting issues task force, who delivered preparatory input and contributions to this document: Jane Bare, Christian Bauer, Anne-Marie Boulay, Cécile Bulle, Mattia Damiani, Jo Dewulf, Johannes Drielsma, Peter Fantke, Rolf Frischknecht, Michael Hauschild, Olivier Jolliet, Annie Levasseur, Xun Liao, Jan Paul Lindner, Danielle Maia de Souza, Llorenç Milà i Canals, Chris Mutel, Laure Patouillard, Stephan Pfister, Massimo Pizzol, Leo Posthuma, Valentina Prado, Ralph Rosenbaum, Abdelhadi Sahnoune, Serenella Sala, Thomas Sonderegger, Franziska Stoessel, Marisa Vieira, and Bo Weidema.

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3. Greenhouse gas emissions and climate change impacts

Annie Levasseur, An de Schryver, Michael Hauschild, Yuki Kabe, Abdelhadi Sahnoune, Katsumasa Tanaka, Francesco Cherubini

3.1 Scope

Life-cycle assessment (LCA) studies quantify the climate change impacts of greenhouse gases emissions due to human activities by aggregating them into a common unit, e.g., CO_2-equivalent (Hellweg and Milà i Canals 2014). Since its publication in the First Assessment Report (AR) of the Intergovernmental Panel on Climate Change (IPCC) in 1990, global warming potential (GWP) has been the default metric used as characterization factor in life cycle impact assessment (LCIA) methods. GWP is an integrative measure defined as the integrated radiative forcing of a gas between the time of emission and a chosen time horizon (TH), relative to that of CO_2. The IPCC introduced GWP as follows: "It must be stressed that there is no universally accepted methodology for combining all the relevant factors into a single global warming potential for greenhouse gas emissions. A simple approach has been adopted here to illustrate the difficulties inherent in the concept" (Houghton et al. 1990). Despite this cautious introduction, GWP100 became the default metric in LCA, as well as in policy and other types of applications. More recently, the IPCC reiterated its view in the 5th AR stating that "the most appropriate metric will depend on which aspects of climate change are most important to a particular application, and different climate policy goals may lead to different conclusions about what is the most suitable metric with which to implement that policy" (p. 710) (Myhre et al. 2013).

The science around emission metrics and climate impacts in general has greatly evolved since 1990, but few of these advancements have been incorporated into LCIA methods. Except for the adoption of the updated GWP characterization factors (CF) from the series of IPCC assessment reports, the LCA community has not kept up with the development in climate science. The universal and uncritical use of GWP100 has received various criticisms (Fuglestvedt et al. 2003; Fuglestvedt et al. 2010; Shine et al. 2005; Shine 2009; Shine et al. 2007). Several alternative metrics are available from climate science and environmental economics (e.g., Johansson 2012; Manne and Richels 2001; Peters et al. 2011; Shine et al. 2015; Sterner et al. 2014; Tanaka et al. 2009; Wigley 1998), with the global temperature change potential (GTP) being the most influential alternative (Shine et al. 2005). Thus, a deep understanding of the physical meaning of GWP100 is lacking in LCA, as too, the option to use other types of CFs and consider contributions from Near-Term Climate Forcers (NTCFs, like ozone precursors and aerosols). The aggregation to a CO_2-equivalent is challenging because it groups together gases with lifetimes ranging from a few years to several thousands of years. For instance, emissions of well-mixed greenhouse gases (WMGHG) with long lifetimes, like carbon dioxide (CO_2), are dominant in determining long-term temperature changes, while today's emissions of gases with shorter lifetimes, like methane (CH_4) or NTCFs, are important in determining the rate of climate change and less relevant for the longer-term impacts (Pierrehumbert 2014; Rogelj et al. 2014; Shoemaker & Schrag 2013; Smith et al. 2012). There is no single metric that can adequately assess the different contributions of climate forcing agents to both the rate of climate change and the long-term temperature increases. LCIA methods should therefore reflect the complexity of the climate system response to the variety of forcing agents and consider the multiple perspectives of climate change impact dynamic.

3.2 Impact pathway and review of current approaches and indicators

Emissions of CO_2, other GHGs, aerosols, and ozone precursors affect the radiation absorption properties of the atmosphere. The resulting change in temperature affects both natural ecosystems and human societies in multiple ways as illustrated in Figure 1. The resulting damages depend both on the rate with which the climate change occurs in the short-term perspective, and on the long-term temperature increase, which determines the climate of the planet in the centuries to come. The former is decisive for the ability of ecosystems to move or adapt to the climate conditions, including the possibilities that human societies have to accommodate to the changing climate. The latter, on the other hand, will influence aspects like sea level rise and long-term temperature increase. Other types of human disturbances, such as albedo changes induced by land cover changes may also affect the climate. However, they are highly localized and case-specific, thus posing challenges for default inclusion in LCA. Methods and metrics for the quantification of their associated impacts on climate are still under development. They are therefore left out from the scope of this work and were not discussed during the workshop.

In addition to the well-known WMGHGs, human activities perturb the climate system through emissions of NTCFs, such as nitrogen oxides (NOx), carbon monoxide (CO), volatile organic compounds (VOCs), black carbon (BC), organic carbon (OC), and sulphur oxides (SOx). Some of these pollutants are precursors to the formation of tropospheric ozone (NOx, CO, VOCs), others are primary aerosols (BC, OC) or precursors to secondary aerosols (NOx, SOx) that can either absorb (BC) or scatter (SOx and OC) solar radiation. These species affect climate through many nonlinear chemical and physical interactions, including changes in methane lifetimes, cloud cover and other indirect effects (Myhre et al. 2013). These short-lived compounds have lifetimes in the atmosphere of days to weeks, and they are commonly classified as near-term climate forcers (NTCF) reflecting that their contribution to climate change is particularly relevant in the first years after their emission. Because they are too short-lived to become well mixed in the atmosphere, their effects on climate have strong spatial and temporal heterogeneities, with varying regional impact dynamics that are dependent on the region of emission. While their contribution to the rate of temperature increase can be important, the contribution of today's emissions to long-term climate change is modest. Some NTCFs are cooling agents and thus have negative characterization factors, like SOx and OC. We note that the latest IPCC report includes among the NTCFs also GHGs with short lifetimes. However, with the term NTCFs, we here refer to those species like aerosols and ozone precursors that are not well mixed in the atmosphere and their climate impacts are therefore dependent on the location of the emission.

In contrast, WMGHGs (e.g., CO_2, CH_4, N_2O, SF_6, CFCs, and other halocarbons) have a lifetime of years to millennia, which means that they have time to become well mixed in the atmosphere. They cause a global climate impact that is largely independent from the emission location. In addition to their ability to contribute to the rate of climate change, some gases contribute more than others to the long-term increase in the global temperature.

The impact pathway of climate change is very broad and complex in the sense that it involves multiple impacts of both regional and global nature and extends from the shorter term into the more distant future (Figure 3.1 presents a very simplified version).

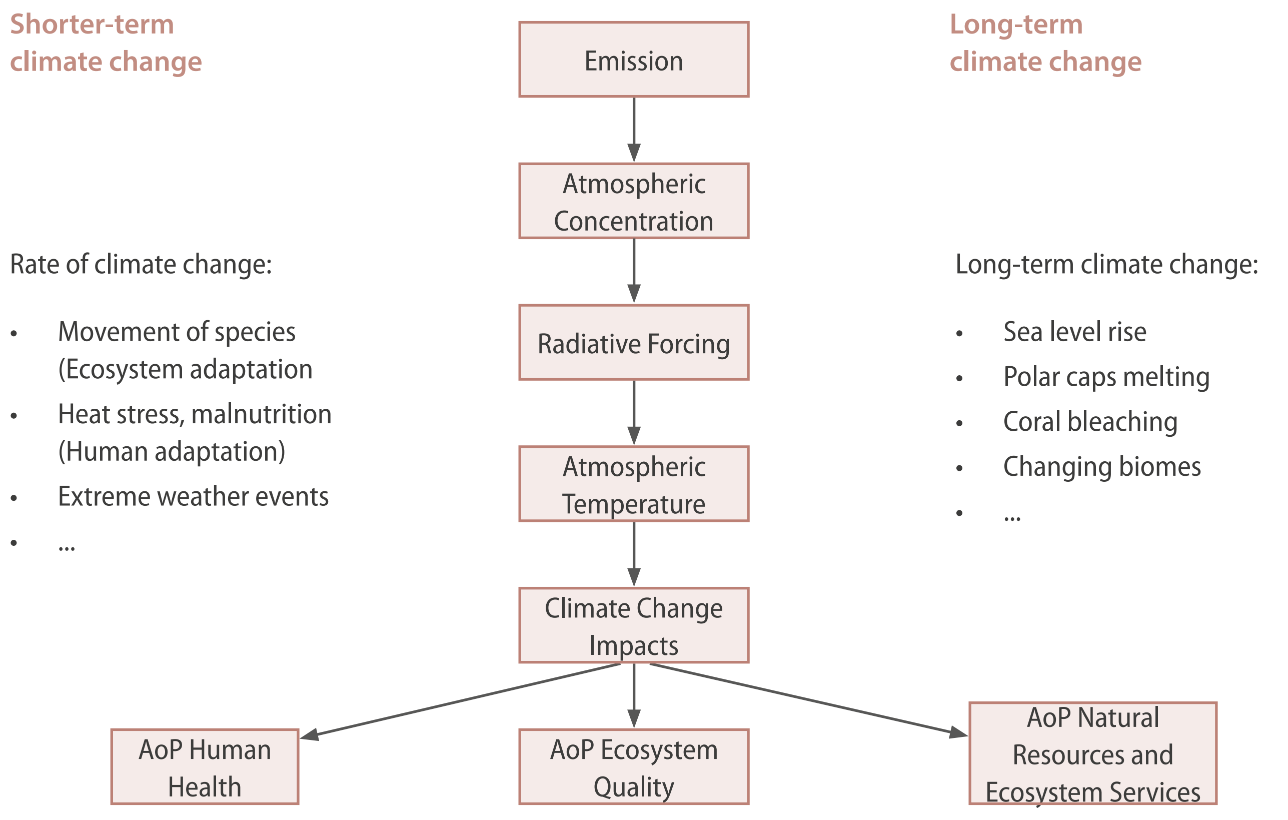

Figure 3.1: Simplified impact pathway for climate change (AoP: Area of protection)

Impact category indicators provided by the IPCC are defined early in the impact pathway (Figure 3.1):

Global warming potential (GWP) uses the emission's radiative forcing as an indicator (W.m-2.kg-1), integrates it (the absolute GWP (AGWP), in W.yr.m-2.kg-1), and then divides the value at a specific point in time, the time horizon (TH), by that of CO_2. It is thus a normalized cumulative metric.

Global temperature change potential (GTP) is an instantaneous normalized metric and uses as an indicator the global average temperature increase of the atmosphere at a future point in time that results from the emission (the absolute GTP (AGTP), in K.kg-1). The temperature increase is determined for a specific TH and is divided by the temperature increase caused by an equivalent amount of CO_2. Both GWP and GTP thus express results in terms of g CO_2-equivalent. The benefit of a metric reflecting the temperature change is that it is closer to actual impacts compared with radiative forcing, even though its quantification is more uncertain than GWP. The temperature change is also a target measure commonly addressed in climate policies (e.g., 2 degree target endorsed by the Paris agreement).

Expressions and parameters for calculation of GWP and GTP can be found in the IPCC 5th AR (Myhre et al. 2013) where values are tabulated for different time horizons. Figure 3.2 shows both instantaneous radiative forcing and AGTP functions for two climate forcers having different lifetimes and radiative efficiencies. For GWP, the area under the curve for the considered GHG is divided by the area under the curve for CO_2 (Figure 3.2a), while for GTP, the value on the curve for the considered GHG is divided by the value on the curve for CO_2 (Figure 3.2b). GWP may be perceived as more consistent with an overall LCIA framework, as in many other impact categories the fate of pollutants is integrated over time. On the other hand, GTP is usually more appropriate to assess the impacts at the end of a target period.

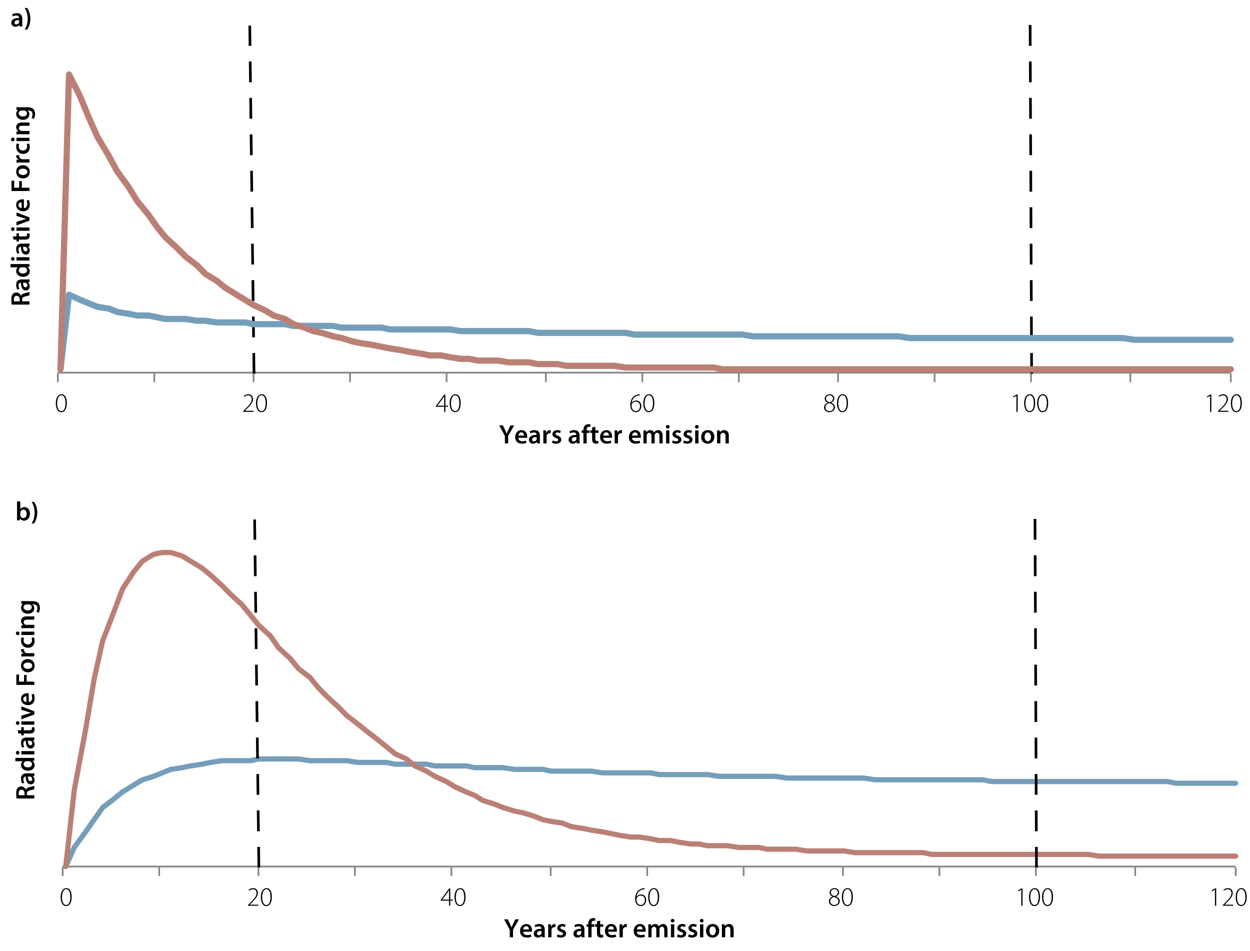

Figure 3.2: . Instantaneous radiative forcing and AGTP functions used to calculate GWP and GTP for two climate forcers having different lifetimes and radiative efficiencies. s

The blue curve is CO_2, the red curve is for a gas with the same lifetime as methane.

In Figure 3.3, the global emissions in 2008 are characterized with GWP and GTP using different time horizons to provide an overview on how results can be sensitive to emission metrics. The calculated climate change impact from emissions of NTCFs and GHGs with short lifetimes, like CH_4, declines with increasing time horizons whereas the impact from WMGHGs with longer lifetime lingers on. The decline is more rapid for GTP rather than GWP, as the former is an instantaneous metric and thus has no memory of previous warming, while the latter is a cumulative metric that accounts for warming occurring during the course of the selected time horizon and carries forth the high forcing from the early phase. Evidently from Figure 3.3, CO_2 is the main concern when it comes to assessing long-term effects, while short-lived gases are relevant for shorter-term changes in the climate.

Rapid short term temperature changes and long-term temperature changes are associated with different types of damages, which cannot be disentangled when aggregating all species into a single indicator or impact category. Two distinct and complementary impact categories can facilitate a more comprehensive and user-relevant endpoint assessment in LCA. The proposed approach covers long-term temperature increase (dominated by long-lived WMGHGs, relevant for sea level rise, irreversible changes of climate, etc.) as well as shorter term rate of change (strongly influenced by NTCFs and short-lived WMGHGs, more relevant for impacts on ecosystems and human societies due to rapid temperature changes).

3.3 Process and criteria applied to select the indicator(s)

The current practice in assessing climate change impacts in LCA often relies on a single indicator. The state of the art in climate science summarized by the IPCC 5th AR is at odds with this approach. Different from other impact categories, climate change has the advantage to rely on an authoritative source of information like the IPCC. The indicators considered in this work are therefore the same as those reported in Chapter 8 of the 5th IPCC assessment report (Myhre et al. 2013), i.e., GWP20, GWP100, GTP20, GTP50, and GTP100 (Table 3.1). They are evaluated according to their environmental relevance (to cover the broad spectrum of relevant long- and shorter-term impacts) and reliability (associated uncertainty).

Table 3.1 summarizes the meaning and possible use in LCA of the indicators presented in the latest IPCC report. The different indicators and TH represent different characteristics of the climate system response to emissions, and assign different weights to forcing agents depending on the type of climate impact they relate to. Aggregation of all forcing agents to CO_2-equivalents through a single characterization factor is always challenging because it groups together species with different perturbation

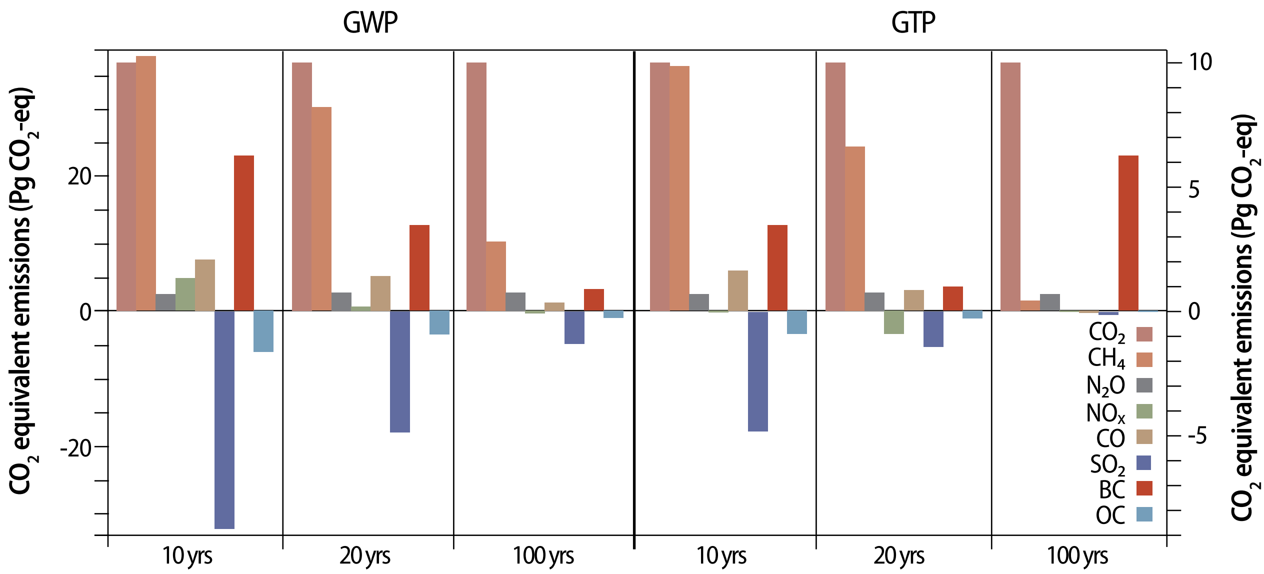

Figure 3.3: Global anthropogenic emissions (2008) of WMGHGs and NTCFs characterized by GWP and GTP for different time horizons (taken from Myhre et al. 2013)

lifetimes that cause heterogeneous impact profiles. When all WMGHGs are combined in one single impact category, mitigation options are quantified on the basis of total CO_2-equivalents, independently of the type of emission that is reduced. However, mitigation of short-lived species or CO_2 achieves different goals which are not equivalent in terms of climate system responses (Pierrehumbert 2014; Shoemaker and Schrag 2013). The same net reduction of the total aggregated emissions will have different climate effects depending on whether it comes from a reduction in long-lived or short-lived species. If emissions of long-lived gases continue to rise, the mitigation of short-lived species would temporarily reduce the rate of warming but will not avoid the breaching of specific warming thresholds (Allen and Stocker 2014; Bowerman et al. 2013). As long as the concentration of CO_2 is allowed to keep growing, the reaching of those thresholds is only temporally postponed (Pfister and Stocker 2016; Stocker 2013). This means that any delay in mitigation of CO_2 emissions will lead to nearly irreversible warming (Allen et al. 2009; Friedlingstein et al. 2014; Matthews and Caldeira 2008; Solomon et al. 2009), whereas this is not the case for short-lived species (Allen 2015; Bowerman et al. 2013; Pierrehumbert 2014; Rogelj et al. 2014).

It is impossible to identify a single indicator that can produce a balanced representation of this complexity. Any choice that works for one dimension of the climate system, such as shorter-term impacts related to the rate of temperature change, inevitably risks overlooking others, such as long-term impacts related to the total temperature increase. For instance, indicators that have a short TH and/or are time-integrated (such as GWP20 and GWP100) attributes higher relative importance to short-lived species than those that are instantaneous and with longer THs (such as GTP100), while the latter mainly considers contributions from CO_2 and other long-lived gases. Although based on the same TH, GWP100 and GTP100 are substantially different. GWP100 underestimates the long-term (persistent) effects. Because numerical values of GWP100 are usually similar to those of GTP with a TH of about 40 years (Allen 2015), GWP100 could be seen as a proxy for the potential temperature rise from short-lived WMGHGs in about four decades. On the other hand, GTP100 is a better option for assessing temperature changes on a longer period (i.e., 100 years).

The possibility to use more than one impact category in LCA for climate change will enhance the understanding of different types of impacts from climate forcing agents associated with products and services. The adoption of two complementary perspectives, one focused on the shorter-term rate of warming (next decades) and the other on long-term temperature rise (next centuries), will improve the capacity of LCA to inform decision makers and is a step towards reducing the gap between LCIA methods and climate science. An alternative option would have been the definition of two different sets of pollutants. For instance, within a context of emission accounting, some explore a multi-basket approach in which gases with similar lifetimes are grouped together and separately assessed, e.g., a short-lived and long-lived basket (Daniel et al. 2012; Fuglestvedt et al. 2000; Smith et al. 2012). This approach has the advantage of avoiding the aggregation of all WMGHGs to common units. However, it is dropped here in favor of the use of two impact categories, because the latter can account for both the (relatively small) contributions of short-lived species to long-term impacts and the contributions of long-lived gases to shorter-term climate change. These two impact categories need an independent set of characterization factors. We consider as possible options the metrics available in

Table 3.1: IPCC 5th AR climate change impact indicators

Indicator & TH	Impact measured	Interpretation
GWP 20	Radiative forcing; cumulative	Assesses warming over the next two decades only; high importance to NTCFs and very short-lived GHGs
GWP 100	Radiative forcing; cumulative	The most common in LCA; represents integrated forcing over 100 years; numerical values are similar to those of GTP40 (i.e. proxy for temperature impacts in about 40 years
GTP 20	Temperature; instantaneous	Measure of potential temperature rise 20 years from today
GTP 50	Temperature; instantaneous	Measure of potential temperature rise 50 years from today
GTP 100	Temperature; instantaneous	Measure of potential temperature rise 100 years from today; numerically similar to GWP with TH of several centuries

the IPCC 5th AR (Table 3.1), and we select the CFs to use according to the following criteria:

- **Shorter-term climate change (targeting the rate of warming)**: GWP is a cumulative metric, and as such it ensures that the forcing from quickly decaying species is taken into account. A TH of 100 years includes most of the perturbation lifetime of CH_4, the major short-lived pollutant and the second contributor (after CO_2) to global radiative forcing in 2011 since pre-industrial times. We recommend the use of GWP100 in quantifying and reporting shorter-term climate change impacts. The other options for assessing shorter-term impacts (GWP20 and GTP20) are equally valid metrics, but they cover only part of the temporal evolution of the impacts from emissions of key short-lived species such as methane. We recommend the use of GWP20 in a sensitivity analysis for assessing shorter-term climate change effects. GTP20 is excluded because as an instantaneous indicator it can overlook contributions from very short-lived species.
- **Long-term climate change (targeting the long-term temperature rise)**: GTP100 is a suitable indicator to use when estimating the temperature rise from GHG emissions one century from today. In terms of numerical values, GTP100 is similar to GWP with a TH of several centuries (the value of TH varies for the different species). We therefore recommend the use of GTP100 as an indicator of long-term climate change impacts. GTP50 is excluded because it has a shorter TH and might underestimate the contributions from long-lived species. Further, the numerical values of GTP50 do not significantly differ from those of GWP100 (numerically similar to GTP40, as mentioned in Table 3.1).

These two impact categories should consider contributions from all WMGHGs. Given the high uncertainty ranges associated with the CFs for NTCFs, these should only be considered in a sensitivity analysis, and only for the shorter-term climate change (as explained in Section 6 below), as their impact on the long-term are negligible.

3.4 Description of selected indicator(s)

Based on the above, we recommend the adoption of two impact categories to better reflect the complexity of climate change:

- One impact category to reflect the shorter-term environmental and human health consequences from the rate of climate change (e.g., lack of human and ecosystem adaptation), with GWP 100 as indicator.
- One impact category to reflect the long-term effects from climate change (e.g., temperature rise, sea level rise), with GTP 100 as indicator.

Table 3.2 describes the two recommended impact categories together with their respective indicator and unit.

In the shorter-term climate change, GWP20 can be used in sensitivity analyses. This metric attributes

Table 3.2: Description of the two selected impact categories with the respective indicators to characterize shorter- and long-term climate change impacts in LCA

Impact category	Shorter-term climate change	Long-term climate change
Time horizon	100	100
Metric	GWP	GTP
Unit	CO_2-equivalents (short)	CO_2-equivalents (long)
Description	Rate of change, assessed with a cumulative metric that covers most impact of CH_4. Numerically similar to a temperature increase in 40 years.	Long-term climate effects, assessed with an instantaneous metric. Targeting the temperature increase within 100 years, which can be seen as a numerical proxy for GWP of several hundreds of years.
Impacts addressed	Heat stress, malnutrition (human adaptation), movement of species (ecosystem adaptation), coral bleaching, changing biomes, etc.	Sea level rise, polar caps melting, etc.

high importance to NTCFs and very short-lived gases, and provide a complementary point of view on the contribution to the near term effects on climate.

The unit to be used for each impact category requires clarification. The use of CO_2-equivalent has the benefit of (i) being well known within society and so easier to understand after years of use and (ii) a reduction in uncertainty (relative to absolute metrics) by dividing through the reference substance. However, it should be clearly noted that these two units cannot be added or combined together, as they express different indicators that are representative of two different (and complementary) impact categories. Thus, special care should be given to the communication of the results. For this reason, we recommend using an additional indication in parentheses, i.e., (short) and (long), respectively, with the units.

One remaining issue that needs to be elaborated upon when choosing indicators from the IPCC table is climate-carbon cycle feedbacks. The changing climate influences the global carbon cycle by influencing the rates of soil respiration and photosynthesis. In climate science, the importance of such climate-carbon cycle feedbacks for future climate projections has received attention through a seminal work of Cox et al. (2000). However, the quantification of climate-carbon cycle feedbacks is fraught with large uncertainties due to the limited scientific knowledge at present (e.g., Friedlingstein et al. 2006). Metric values reported in the main part of Chapter 8 of IPCC 5th AR account for such feedbacks for CO_2 but not for other climate forcers. On the other hand, metric values reported in the supplementary information of Chapter 8 consistently include such feedbacks for all the climate forcers. To be consistent with the treatment of CO_2, we recommend using metrics which also include feedbacks for non-CO_2 GHGs. Including feedbacks for both non-CO_2 and CO_2 provides better and more unbiased impact estimates.

3.5 Model, method, and specific issues addressed

Emission metrics are simplified measures of the climate system response to forcing agents and are based on the outcomes from complex physical models linking emissions to impacts. The CFs from IPCC 5th AR are produced from models that i) give the temporal evolution of radiative forcing in response to an instantaneous emission of a climate forcer and ii) yield the temporal evolution of global-mean temperature change as a result of changes in radiative forcing. While computation of GWP values requires only the first type of models, GTP needs both. Below is a short description of the models used in the latest IPCC report to compute GWP and GTP values. Further technical details can be found in Section 8.SM.11 of IPCC 5th AR.

1. **Derivation of the radiative forcing impact profile (used in GWP and GTP computations):**

   The model developed for CO_2 is the most elaborate one because of the complexities in carbon cycle processes relevant to the atmospheric removal of CO_2: saturation of oceanic CO_2 uptake with rising atmospheric CO_2 concentration, CO_2 fertilization of land biosphere, and climate impacts on soil respiration and biological production, to name a few (Ciais & Sabine 2013). IPCC 5th AR employs an impulse response function, a mathematical model that gives a time evolution of the global-mean CO_2 concentration in response to an atmospheric release of CO_2. The impulse response function consists of three terms governed by distinct decay time constants and one time-invariant constant term that represent a variety of carbon cycle processes operating on a range of time scales. The time constants are tuned to the output from several more complex models describing carbon cycle processes, including the aforementioned complexities (Joos et al. 2013). One can translate the time evolution of the atmospheric CO_2 concentration into the temporal change in the CO_2 radiative forcing by using a CO_2 radiative efficiency: a measure of the radiative forcing change due to an incremental change in the CO_2 concentration. The radiative efficiency used in IPCC 5th AR is the estimate for the background CO_2 concentration in year 2010. This matters because the current atmospheric CO_2 level is sufficiently high that the increase in radiative forcing due to an incremental increase in CO_2 concentration decreases with rising atmospheric CO_2 concentration in the background (Reisinger et al. 2011). From the perspective of LCA, the 2010 atmospheric CO_2 level can be considered as a constant reference state to estimate the characterization factors for climate change. Less complicated models are used for non-CO_2 climate forcers. Concentration changes of non-CO_2 forcers are modeled by only simple exponential decays whose time scales are identical to the respective perturbation lifetimes, (Solomon et al. 2010; and available in Table 8.A.1 of IPCC 5th AR). Such concentration changes are linearly related to the changes in radiative forcing by using the respective radiative efficiencies, which can be obtained from the same IPCC table (8.A.1). Notable exceptions are the models for CH_4 and N_2O, in which indirect effects are taken into account (see Sections 8.SM.11.3.2 and 8.SM.11.3.3 of IPCC 5th AR).

2. **Derivation of the temperature impact profile (used in GTP computations only):**

   A time evolution of radiative forcing is related to that of global-mean temperature change through a climate model, which is an impulse response function comprising the following two terms: one governed by a small time constant and the other by a large time constant (Boucher and Reddy 2008). Such time constants crudely represent the climate response involving the mixed layer of the ocean and that associated with the deeper layers, respectively. The time constants are calibrated with a more complex model and given in Table 8.SM.9 of IPCC 5th AR. The equilibrium climate sensitivity assumed in this model is 3.9°C, an asymptotic temperature change in response to the doubling of atmospheric CO_2 concentration from preindustrial levels.

3.6 Characterization factors

3.6.1 CFs for WMGHGs and NTCFs

It is recommended to use GWP100 for the shorter-term impact category related to the rate of temperature change, and GTP100 for the long-term impact category related to the long-term temperature rise for WMGHGs. For the shorter-term climate effects, a sensitivity analysis should also include results from NTCFs and applying GWP20 (in addition to GWP100) as CFs.

IPCC directly computes CFs for WMGHGs but gathers from the climate science literature those for NTCFs. IPCC includes some WMGHGs with short lifetimes in the group of NTCFs. To avoid overlapping between the two groups, we reiterate that, in this work, the term NTCFs is only used for species that are not well-mixed once emitted to the atmosphere because of their very rapid decay (from few days to few months). These species are black carbon (BC), organic carbon (OC), nitrogen oxides (NOx), sulphur oxides (SOx), volatile organic compounds (VOCs), and carbon monoxide (CO).

CFs for WMGHGs to be used in LCA are those with feedbacks included (Table 3.3). Values with feedbacks are preferred to ensure consistency, as feedbacks are already included for CO_2. Although this leads to higher uncertainty ranges, "it is likely that including the climate–carbon feedback for non-CO_2 gases as well as

Table 3.3: Characterization factors for the short-term and long-term climate change impact categories for a selection of WMGHGs

Values include climate-carbon feedbacks. See Table 8.SM.15 in the supplementary information of WGI Chapter 8 of the IPCC for the remaining gases (Myhre et al., 2013). This should not be confounded with Table 8.A.1 of the appendix that includes feedbacks for CO_2 only and not for the other WMGHGs.

WMGHG	Chemical formula	Lifetime (years)	Shorter-term climate change	Long-term climate change	
			GWP20[2]	GWP100	GTP100
Carbon dioxide	CO_2	Indefinite	1	1	1
Methane[1]					
Biogenic	CH_4	12.4	86	34	11
Fossil	CH_4	12.4	87	36	13
Nitrous oxide	N_2O	121	268	298	297
HCF-134a	CH_2FCF_3	13.4	3 790	1 550	530
CFC-11	CCl_3F	45	7 020	5 350	3 490
PFC-14	CF_4	50 000	4 950	7 350	9 560
Sulphur hexafluoride	SF_6	3 200	17 783	26 087	33 631

[1] Values for biogenic methane do not include contributions from methane oxidation to CO_2, while those for fossil methane do. We did not discuss how biogenic CO_2 should be treated in the life cycle inventory step during this workshop.

[2] For sensitivity analysis only.

for CO_2 provides a better estimate of the metric value than including it only for CO_2" (Myhre et al. 2013).

LCA has so far overlooked contributions from NTCFs. Although they are usually associated with higher uncertainty than WMGHGs, they can have a significant impact in the short-term and their consideration is thus recommended in a sensitivity analysis using the ranges of metric values in Table 3.4. This table is produced from the CFs in the appendix of IPCC WGI Chapter 8, which summarizes values taken from the literature. For some species, there are available metric values that also include contributions from aerosol-cloud interactions. However, they are currently excluded because of two main reasons: i) uncertainty, as modeling of secondary aerosol and cloud feedbacks is still highly uncertain (Carslaw et al. 2013); ii) consistency, as these contributions are not factored in for all the CFs available for the different NTCFs. GTP100 CFs are missing for some NTCFs, for which only GWP20 and GWP100 are given. This will have minor influence on the long-term climate change impact category as NTCFs are very short-lived and would have very little contribution to the instantaneous temperature measured with GTP100. It is normally not necessary to consider NTCFs in the long-term impact category.

3.6.2 Uncertainty in CFs of WMGHGs

Characterization factors have uncertainty in the numerator and the denominator. The numerator, that is the absolute global warming potential (AGWP) of the specific gas, is affected by uncertainties in lifetimes of the gas and the specific radiative efficiency, with the inclusion of indirect effects that can further increase uncertainty. The denominator, i.e., the reference gas CO_2, has uncertainties in the impulse response function used to describe the atmospheric CO_2 concentration change following a pulse emission, which is sensitive to model parameterization of the carbon cycle mechanisms, and background state of the climate system. The IPCC uses the CO_2 impulse response function that is the outcome of a multi-model intercomparison project to mitigate these sources of uncertainty (Joos et al. 2013). For instance, uncertainty ranges for the AGWP of CO_2 are +/- 18% and +/- 26% for 20- and 100-year time horizons, respectively. These uncertainties are present in GTP as well, with the additional uncertainties in ocean heat uptake and climate sensitivity. The uncertainty mainly arises from the climate sensitivity, an asymptotic temperature increase in response to doubling atmospheric CO_2 concentration from its preindustrial level. Due primarily to uncertainties in cloud-related processes (Boucher et al. 2013), there is a substantial spread in the 95% confidence range of climate sensitivity, which is from 2.0K to 4.5K. However, the uncertainty in climate sensitivity does not exhibit itself to a full extent in GTP formulation, because it is a ratio of temperature changes and the influence of the climate sensitivity cancels out. For further details on the uncertainties in GWP and GTP, see (Joos et al. 2013; Reisinger et al. 2010).

Table 3.4: CFs for NTCFs for sensitivity analysis

Source: (Myhre et al. 2013)

NTCF	GWP20	GWP100	GTP100
NO_x [1]	–108 ± 35	–29 ± 9	-2 ± 1.9
CO [2]	7.8 ± 2.0	2.1 ± 0.5	-0.2 ± 0.1
VOC [3]	18.7 (±7.5)	5.5 (±2.3)	0.8 (±0.4)
SO_x [4]	-141	-38	-5
OC [5]	–160 (–60 to –320)	-43 (-17 to -86)	-6.7 ± 1.9
BC [6]	3 200 (270 to 6 200)	846 (94 to 1 600)	120 (5 to 313)

[1] Table 8.A.3, first ranges (no aerosol) of the bottom line representing global averages. All values are on a per kilogram of nitrogen basis. GWP100 is adjusted to account for updated values for the reference gas CO_2 (for TH = 20 years the changes are negligible).

[2] Table 8.A.4, first ranges (no aerosol) of the bottom line representing global averages. GWP100 is adjusted to account for updated values for the reference gas CO_2 (for TH = 20 years the changes are negligible).

[3] Table 8.A.5, second last line (the numbers of the last line fall within this range). Factors represent the average values of the global impacts from the major emitting regions. GWP100 and GTP100 are adjusted to account for updated values for the reference gas CO_2 (for TH = 20 years the changes are negligible).

[4] Table 8.SM.17 in the Supplementary material. No ranges available.

[5] Table 8.A.6, second last line. Ranges for GWP100 are gathered directly from the original source (Bond et al., 2011), as they are misspelled in the IPCC Table. GWP100 is adjusted to account for updated values for the reference gas CO_2 (for TH = 20 years the changes are negligible).

[6] Table 8.A.6, first line. GWP100 and GTP100 are adjusted to account for updated values for the reference gas CO_2 (for TH = 20 years the changes are negligible).

Figure 3.4: Contribution to impact score of five main GHGs for the three scenarios of the rice case study using the metrics available in the latest IPCC report (with climate-carbon feedbacks)

Functional unit: consumption of 1 kg rice.

Uncertainty in CFs of NTCFs

The confidence level in the characterization factors for NTCFs is lower than that for WMGHGs, especially in the cases in which aerosol-cloud interactions are important (Boucher et al. 2013; Myhre et al. 2013). These emissions are coupled with the hydrological cycle and atmospheric chemistry and involve highly complex processes, which are the result of many opposing effects characterized by different temporal scales (Fuglestvedt et al. 2010). IPCC provides CFs with large uncertainty ranges, which are to be explicitly taken into account in LCA. Given the current status of CFs for NTCFs, we recommend that a sensitivity analysis of the influence of NTCFs on shorter-term climate change using the range of characterization factors for both GWP20 and GWP100 is performed. Results can be shown by taking the CFs representing a best case and a worst case. In the best case, CFs are those at the lowest end of the uncertainty ranges (corresponding to values representing more cooling for species like SOx and OC, and lower warming for species like BC and VOCs). In the worst case, CFs are those at the highest end of the uncertainty range (corresponding to the values with the lowest cooling and larger warming potential).

3.6.3 Spatial variability

Climate impacts from WMGHGs are insensitive to emission regions. The situation changes for NTCFs, whose climate impacts are dependent on the emission location (Collins et al. 2013; Fry et al. 2012). However, there are still significant uncertainties in modeling the sensitivity to emission regions and the spatial differentiation of climate impacts. Metrics that rely on global averages and/or long integration times like GWP100 do not fully represent the temporal and spatial heterogeneities of the responses, although the application of a metric that is first calculated locally and then averaged globally is better than one based on global mean outputs (Lund et al. 2012). Regional specific responses and metrics for NTCFs are also available, but additional studies are required to determine their robustness. LCA can start to adapt to the possible future inclusion of regional climate change impact categories by providing spatial explicit emission inventories. Further, BC and OC emissions are currently missing from the main inventory databases. Although they can be deduced from the amount of particulate matter emitted, databases should facilitate characterization of those species by adding these stressors to the inventories.

3.7 Rice case study application

Climate change impact scores have been calculated for the three scenarios of the rice case study for different metrics and modeling choices. This case study compares rice cultivation, processing, transport, and consumption in three representative locations: rural India, China, and USA-Switzerland (consumed in Switzerland, but imported from the USA)[2]. See Frischknecht et al. (2016) for details about the case study. Figure 3.4 shows the contribution to the results of five main greenhouse gases (carbon dioxide, methane, nitrous oxide, sulphur hexafluoride, and tetrafluoromethane) using all the metrics available from the 5th IPCC AR with climate-carbon feedbacks. Emissions of methane, a short-lived well-mixed GHG, contribute substantially to climate change impacts and are mainly caused by rice cultivation.

Figure 3.5 presents the case study results for the two impact categories recommended in this chapter. GWP100 is used to assess shorter-term climate change impacts related to the rate of temperature change, while GTP100 is for long-term climate change impacts related to the long-term temperature rise. Because methane is a short-lived GHG, its contribution to shorter-term climate change is higher than for long-term climate change. As shown in Figure 4, the contribution of methane to shorter-term climate change impacts is higher for the USA-Switzerland scenario, leading to the second highest score in shorter-term climate change impact category and to the lowest score in the long-term climate change impact category.

Since the rice supply chain causes significant emissions of the NTCFs SO_2, NO_x and black carbon (BC), a sensitivity analysis is performed to see if their inclusion could change the conclusions for the shorter-term climate change impact category. Figures 3.6, 3.7 and 3.8 present the results of the sensitivity analysis performed for NTCFs using GWP20, GWP100, and GTP100. In each of these figures, results are first presented for WMGHGs only, then for NTCFs using lowest ("best case") and highest ("worst case") CF values, and finally for the combined impacts from GHGs and NTCFs. They show that the range of climate change impacts caused by NTCFs can be high, and it depends on the associated uncertainties. Ranking between scenarios is not affected by the inclusion of NTCFs for the best

2 These three scenarios are only for a plausible illustration, and not representative at all of the situation expected in different countries.

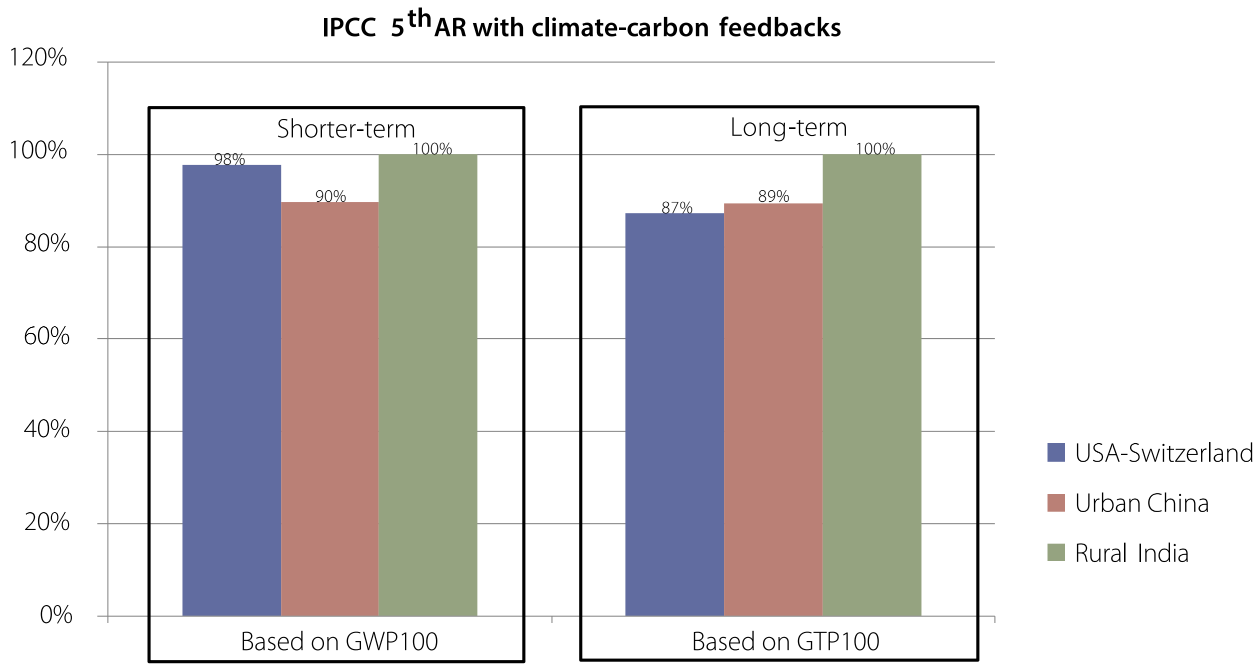

Figure 3.5: Case study results for the three scenarios for the shorter-term climate change (using GWP100) and the long-term climate change (using GTP100) impact categories

case. However, ranking changes for the worst case for GWP20 and GWP100 as the rural India scenario includes high CO and black carbon emissions from the wood stove used to cook the rice. The sensitivity analysis performed using GTP100 shows that NTCFs do not influence significantly long-term climate change impacts. Life cycle inventories are incomplete for all three scenarios regarding NTCFs. Data about black carbon and organic carbon are lacking in the ecoinvent database (Frischknecht et al. 2004). They have been roughly approximated assuming that half of the emissions of PM<10 from the stove is black carbon and the other half organic carbon.

3.8 Recommendations and outlook

3.8.1 Main recommendations

Impact category: To represent the complexity of climate change impacts, more than one impact category is needed. Therefore, in LCA application, we **recommend considering two separate impact categories for climate change (shorter-term related to the rate of temperature change, and long-term related to the long-term temperature rise).**

If practitioners wish to report results based only on one indicator for climate change, we strongly recommend to (a) at least note the possible sensitivity of their results to the specific indicator chosen, and (b) provide justification for their choice and clearly communicate the meaning of the results (e.g., whether they target shorter-term impacts associated with the rate of temperature change or long-term impacts associated with the long-term temperature rise).

Shorter-term climate change indicator

We recommend using GWP100 as the indicator for the shorter-term climate change impact category for WMGHGs. Although there is no scientific basis to recommend GWP20 versus GWP100, the use of GWP100 provides continuity with LCA practices and ensures that most of the period in which methane, the major contributor to shorter-term climate change impacts, exerts its forcing is covered.

We recommend performing a sensitivity analysis including NTCFs and using GWP20 in addition to GWP100. For shorter-term impacts, GWP20 is the metric among those available in the latest IPCC report that represents the highest potential contribution from NTCFs.

We excluded GTP20 because it generally gives results between GWP20 and GWP100 (so, adding little information to the sensitivity analysis) and might overlook the contribution of very short-lived species (as it is an instantaneous metric).

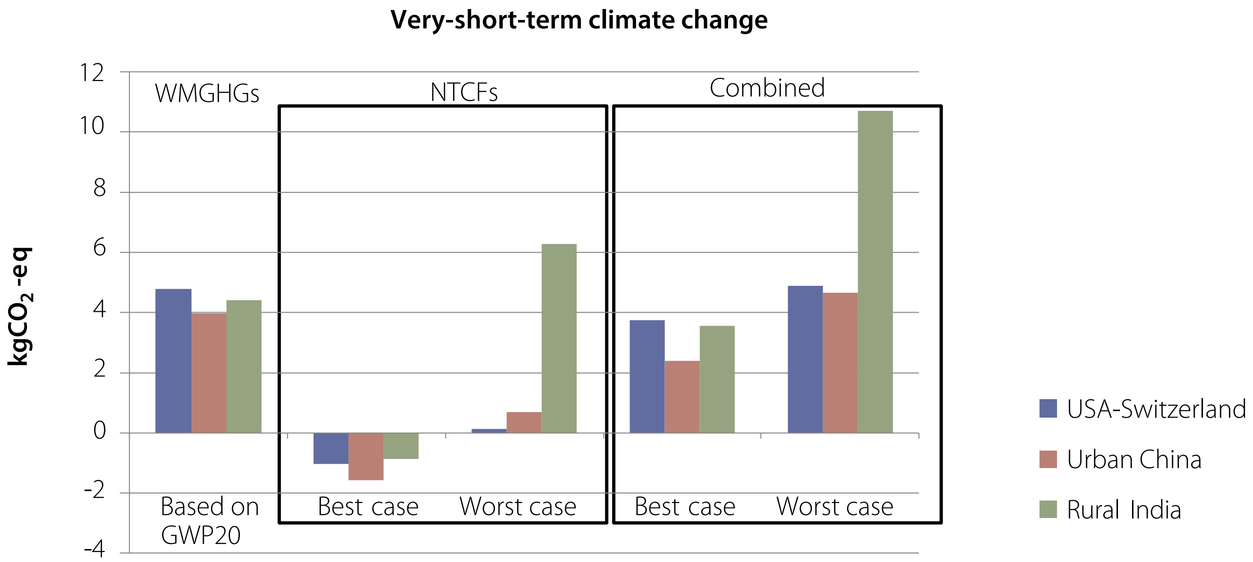

Figure 3.6: Sensitivity analysis for NTCFs using GWP20

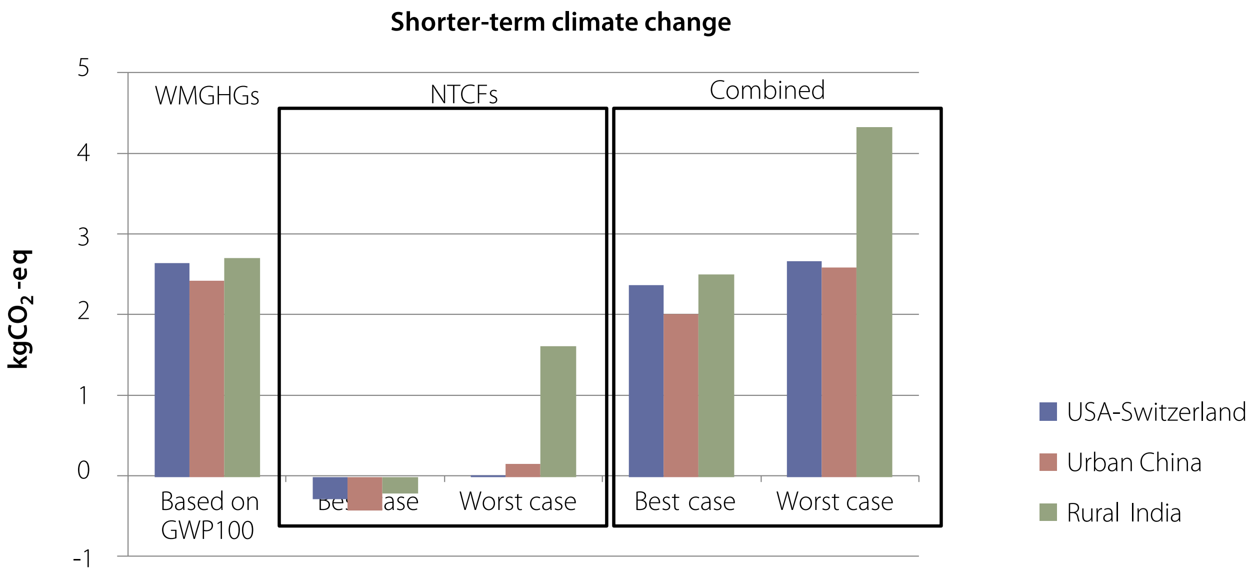

Figure 3.7: Sensitivity analysis for NTCFs using GWP100

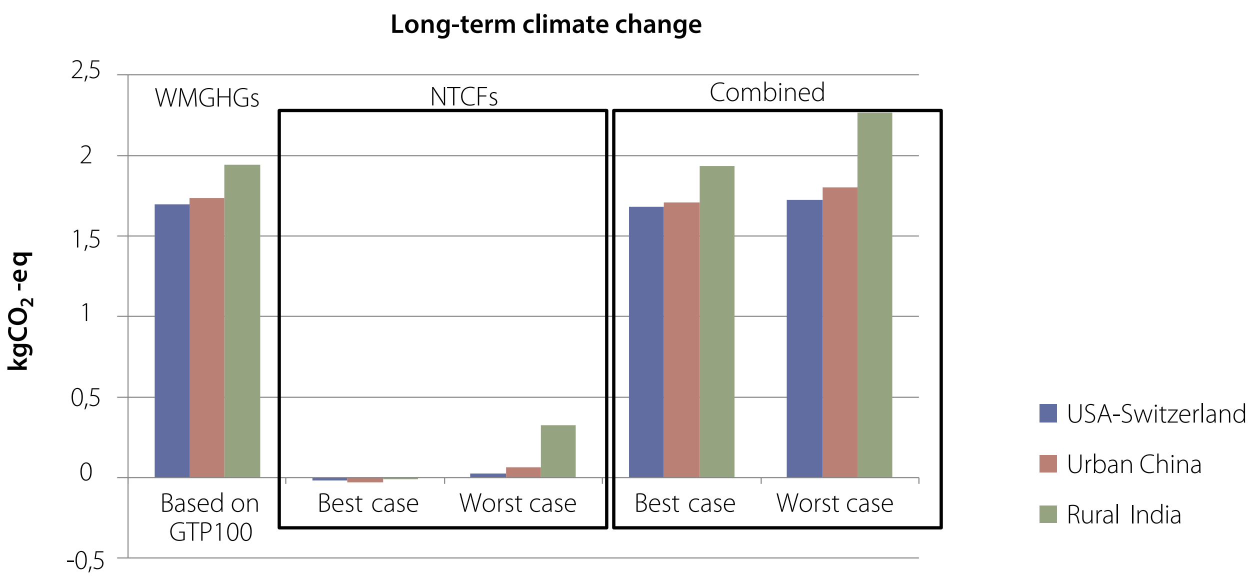

Figure 3.8: Sensitivity analysis for NTCFs using GTP100

Long-term climate change indicator

We recommend the use of GTP100 as proxy for long-term impacts because it is an instantaneous indicator targeting potential temperature rise 100 years in the future.

We exclude GTP50 because it leads to similar conclusions as GWP100.

Use of climate-carbon cycle feedbacks: According to the IPCC (Myhre et al. 2013), including climate-carbon cycle feedbacks for both non-CO_2 GHGs and CO_2 provide a better and consistent estimate. **It is recommended to use metrics including climate-carbon cycle feedbacks for all climate forcers.**

3.8.2 Judgement on quality

The IPCC WG I is high quality and robust reference to provide the basis for climate change impact assessment in LCA. Recommended CFs for WMGHGs are rather certain and of high quality, while CFs for NTCFs are subject to higher uncertainties and regional variability. Approaches and CFs used in LCA should be revised when the IPCC 6th AR is published in order to use the most up-to-date values and climate science insights.

3.8.3 Applicability, maturity, and good practice for factors application

The use of two complementary impact categories in LCA is an element of novelty with respect to the traditional practice, which is based on the use of a single indicator for climate change (usually GWP100). The proposed refinement will certainly require updates of CFs in common database and software providers and a transition phase for practitioners to adapt to the new approach. However, the availability of characterization factors in the IPCC 5th AR makes this transition relatively easy. Modest adaptation efforts will ensure an important step forward in the robustness and relevance of climate change impact assessment in LCA. It would also help avoid impact shifting that may occur when some climate forcing agents are excluded or a single metric is applied, and provide better information to society and decision makers about climate change effects of products and systems.

In LCA applications, we thus recommend the use of the two impact categories described above, as the selection of a single metric or impact category always embeds the risk of providing partial information. If practitioners wish to report results based only on one indicator for climate change, for instance in carbon footprint or standards, we strongly recommend they provide justification for their choice and transparently communicate on the meaning of the results.3

In some LCA studies, part of the emissions may occur only after a few decades in time, for example, when assessing long-lived products, construction products, or landfilling activities. It is acknowledged that in these cases, an inconsistency may arise when assessing all life cycle emissions with both impact categories (GWP100 and GTP100), as all emissions are assumed to happen at the same time. This is a topic that concerns most impact categories and LCA in general, and will be thoroughly addressed as a crosscutting issue in the next phase of the Global Guidance project.

3.8.4 Link to inventory databases

Applying recommended CFs to the case study highlighted the lack of inventory data for two NTCFs in the ecoinvent database (Frischknecht et al. 2004), i.e., black carbon and organic carbon. Performing a sensitivity analysis on NTCFs without BC and OC is not recommended because it may increase the relative importance of cooling NTCFs compared to others since BC has a high CF. There is thus a need to generate information about BC and OC emissions in life cycle inventory databases.

3.8.5 Next foreseen steps

The LCA community should closely follow updates on the topic of climate impact quantification, in particular as the climate community is increasing the robustness of the CFs for NTCFs. Regional climate change categories can also be formulated in the future. We recommend that inventory databases should already adapt by adding black carbon and organic carbon. Inventory spatialization is also becoming important for the climate change category, and future emission

3 Minority statement about applicability: One participant expressed concerns regarding the implications of recommending two impact categories for climate change for practical applications of LCA. This participant suggested that additional guidance on how to handle these two impact categories (when performing carbon footprinting, product labeling, or ecodesign) would be useful for practitioners. This guidance would (i) improve clarity when communicating to consumers only one single impact category and (ii) improve decision making in eco-design. Allowing 'pick and choose' for communicating one climate change impact category, the risk exists that different climate change labels present different information with the same unit applied. For example, for these specific applications it could have been recommended that GWP100 is always reported (this to allow a comparison with previous studies) and GTP100 can be excluded for communication only when the impact category indicator results between the two climate change impact categories are similar (e.g., differ with less than 10%). It is acknowledged that this type of guidelines involves value judgement.

inventories should try to adapt to keep track of emissions locations for NTCFs.

Finally, other types of human intervention such as albedo changes induced by land cover changes may affect the climate. They are highly site- and case-specific, thus posing challenges for default inclusion in LCA, both in terms of inventory items and characterization method. Methods and metrics for the quantification of their associated impacts on climate are still under development. The LCA community is encouraged to follow the development of CFs for inclusion of climate change impacts caused by albedo changes and other land cover related forcers in LCA.

3.9 Acknowledgements

The authors wish to acknowledge the work performed by the global warming task force during the last two years that serves as basis for this workshop. Active members of this task force were, in alphabetical order, Otávio Cavalett, Francesco Cherubini, Jan S. Fuglestvedt, Thomas Gasser, Mark Huijbregts, Daniel J.A. Johansson, Susanne V. Jørgensen, Annie Levasseur, Marco Raugei, Andy Reisinger, Greg Schively, Anders Strømman, and Katsumasa Tanaka. The work done through this task force is summarized in Levasseur et al. (2016) and Cherubini et al. (2016).

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4. Health impacts of fine particulate matter

Peter Fantke, John Evans, Natasha Hodas, Joshua Apte, Matti Jantunen, Olivier Jolliet, Thomas E. McKone

4.1 Scope

A number of health studies, in particular the global burden of disease (GBD) project series (Lim et al. 2012), reveal the significant disease burden posed by fine particulate matter ($PM_{2.5}$) exposures indoors (household and occupational buildings air) and outdoors (ambient urban and rural air) to the world population. However, clear guidance is currently missing on how health effects associated with $PM_{2.5}$ exposure can be consistently included in the SETAC/UNEP framework for LCIA (Fantke et al. 2015). This chapter provides a consistent modeling framework for calculating characterization factors for emissions of primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors indoors and outdoors as well as a roadmap for further refining this framework for use in LCIA.

4.2 Impact pathway and review of approaches and indicators

4.2.1 Impact pathway

The impact pathway for health effects attributable to exposure to $PM_{2.5}$ from emissions of primary $PM_{2.5}$ or secondary $PM_{2.5}$ precursors (gases which are transformed to $PM_{2.5}$ by oxidation) follows the general LCIA framework proposed by (Udo de Haes et al. 2002) and (Jolliet et al. 2004) for characterizing emissions of air pollutants and is illustrated in Figure 4.1. For characterizing $PM_{2.5}$-related health effects, the impact pathway starts from primary $PM_{2.5}$ emissions or secondary $PM_{2.5}$ precursor emissions into (outdoor or indoor) air expressed as mass of $PM_{2.5}$ or precursor released into air, and follows advective distribution and transformation within and among indoor and outdoor (ambient) urban and rural air compartments yielding the time-integrated mass (or concentration) in air of $PM_{2.5}$. A fraction of this time-integrated $PM_{2.5}$ mass in air is subsequently inhaled by an exposed population, resulting in a cumulative population risk that is expressed as expected disease incidences among the exposed population. Cumulative population risk is typically assessed directly based on $PM_{2.5}$ air concentration, where it is assumed that the $PM_{2.5}$ in air is inhaled by the exposed population. In contrast to many LCIA-considered organic chemicals that have an assumed linear dose-response function, $PM_{2.5}$ has a documented non-linear exposure response for important health endpoints. As a final step of the impact assessment, disease incidences are translated into a metric of damage in the exposed population by accounting for the disease severity.

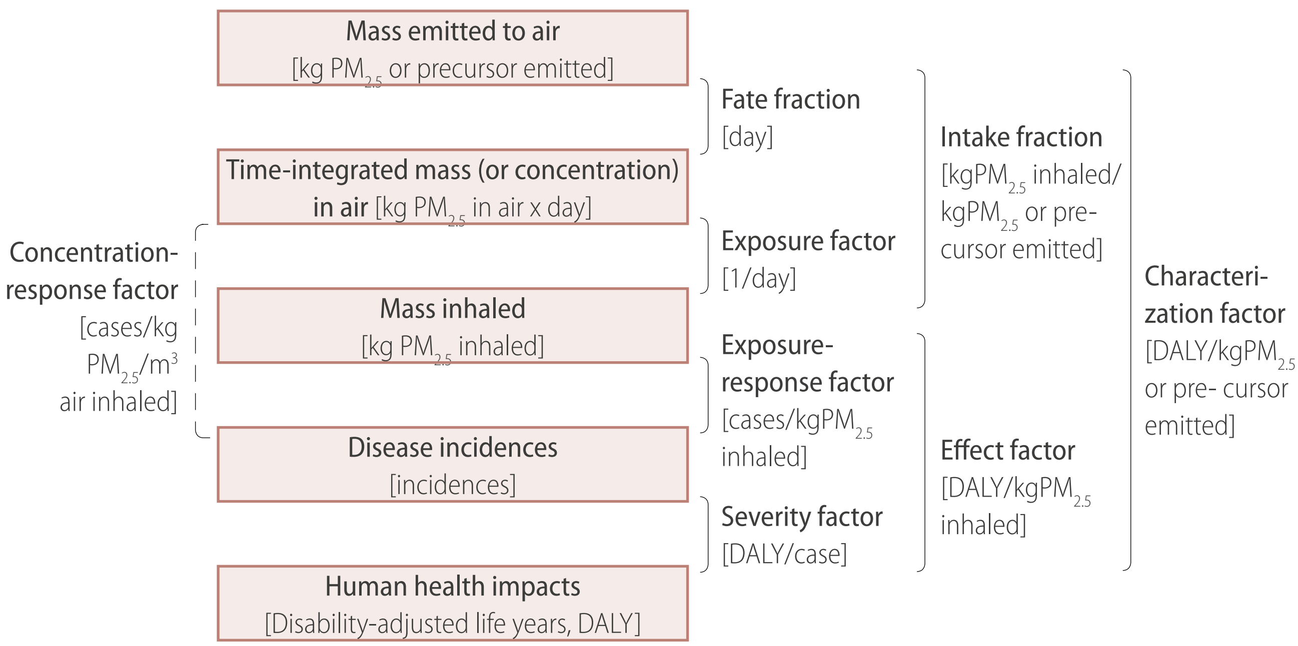

Figure 4.1: Impact pathway followed and framework for assessing human health effects from fine particulate matter ($PM_{2.5}$) exposure in life cycle impact assessment

Adapted from (Fantke et al. 2015).

4.2.2 Background and review of approaches and indicators

Based on an overwhelming body of evidence linking air pollution, particularly $PM_{2.5}$, to negative health effects, a task force was convened to build a framework for consistently quantifying health effects from $PM_{2.5}$ exposure and for recommending $PM_{2.5}$ characterization factors for application in LCIA. In an initial Guidance Workshop in Basel (Switzerland) in 2013, existing literature was reviewed and input from a broad range of internationally recognized experts was obtained and discussed. This workshop identified the main scientific questions and challenges for quantifying health effects from $PM_{2.5}$ exposure in LCIA, and provided initial guidance to the impact quantification framework and process. As a result of the Guidance Workshop and follow-up efforts, the $PM_{2.5}$ LCIA task force developed and published recommendations regarding the process for addressing $PM_{2.5}$ health effects in LCIA (Fantke et al. 2015). These recommendations address (a) the general framework for assessing $PM_{2.5}$-related health effects, (b) approaches and data to estimate human exposure to $PM_{2.5}$ using the intake fraction metric, and (c) approaches and data to characterize exposure-response functions (ERF) for $PM_{2.5}$ and to quantify the severity of the diseases attributed to $PM_{2.5}$ exposure. It was found that a number of complex issues, such as those related to non-linearity of the ERF and the possible need to provide different ERF's for use in different geographic regions, require further analysis. Subsequent task force efforts focused on integrating indoor and outdoor air into a consistent modeling framework, assessing the various aspects influencing indoor intake fractions (Hodas et al. 2016), and how to consistently incorporate indoor and outdoor formation of secondary $PM_{2.5}$ from precursor emissions. All findings and results were discussed in a final workshop, which reflects the current state-of-the-art in addressing health effects from $PM_{2.5}$ exposure in LCIA and is described in the present chapter. How health effects from $PM_{2.5}$ exposure are currently addressed in LCIA methods is discussed in (Humbert et al. 2015).

4.2.3 Evidence of health effects and disease burden

Over the past two decades a substantial evidentiary basis has developed relevant knowledge for assessing the human health impacts of exposure to $PM_{2.5}$. This includes roughly a dozen cohort studies and more than 100 time-series mortality studies conducted in cities around the world. Epidemiological studies of populations exposed to high levels of particulate matter indoors from passive cigarette smoke or use of solid and liquid fuels for cooking and heating also provide evidence relevant for the analysis of mortality impacts of fine particulate matter exposure.

Cohort studies focus on impacts of long-term exposure by examining the differences in mortality rates of populations living in cities with different levels of exposure to pollution. The first cohort study to suggest that exposure to $PM_{2.5}$ adversely affected longevity was the Harvard Six Cities study (Dockery et al. 1993). Analysis of these data, after 15 years of follow-up, indicated that mortality rates were approximately 30% higher in the dirtiest city (Steubenville, Ohio, with 30 µg/m^3 $PM_{2.5}$) than in the cleanest city (Portage, Wisconsin, with roughly 10 µg/m^3) – suggesting that for every 1 µg/m^3 increase in $PM_{2.5}$ levels, mortality rates increased by approximately 1.5%. Using a much larger cohort, Pope and colleagues reported that for each 1 µg/m^3 reduction in ambient levels of $PM_{2.5}$ mortality rates would be reduced by about 0.4%.(Pope III et al. 1995). Over the past decade, not only have these two seminal studies been extended, but several entirely new cohort studies have been conducted, both in the United States and in Europe, Asia, and Oceania. Results from a meta-analysis that encompasses several of these studies show a 1 mg/m^3 increase in $PM_{2.5}$ to be associated with a 0.6% increase in all-cause mortality, and a 1.1% increase in cardiovascular mortality with variability among studies attributable to particle composition, air exchange rates in buildings, demographics, and meteorological variables (Hoek et al. 2013).

Time-series studies assess short-term impacts by examining the relationships between day-to-day variations in air pollution and day-to-day variations in mortality. Virtually all of the studies have found positive associations between daily levels of air pollution and mortality. Although there are both study-to-study differences and regional variations in the quantitative relationship between air pollution and mortality, the consensus among experts is that the time-series literature has clearly established the impact of daily fluctuations in air pollution (especially PM) on mortality. A recent meta-analysis of over 100 time-series studies showed that for all-age all-cause mortality there is a risk increase of 1.04% (95% CI 0.52% to 1.56%) for a 10 µg/m^3 increment in $PM_{2.5}$ (Atkinson et al. 2014). In this meta-review, specific causes of death that are most consistently associated with short-term exposure to $PM_{2.5}$ are respiratory, cardiovascular disease (ischemic heart disease [IHD] and stroke), and chronic obstructive pulmonary disease (COPD).

The integrated exposure-response (IER) function, developed by Burnett et al. (2014) to support the 2010 GBD analysis synthesizing effect estimates from eight cohort studies of ambient air pollution and combining these with effect estimates from studies that involve much higher levels of exposure – such as second-hand smoke, indoor air pollution from cooking (especially with solid fuels) and heating, and active smoking – provided evidence to support risk estimates in the high-concentration region. The epidemiological findings at the heart of the IER are cohort studies that examine the relationship between chronic exposure to fine particulate air pollution and mortality. These studies have found that among adults, cardiovascular mortality from both ischemic heart disease and stroke, as well as mortality from chronic obstructive pulmonary disease and trachea, bronchus, and lung cancers, increase as the exposure to fine particulate matter rises. Among young children, increasing levels of particulate matter have been found to increase mortality from acute lower respiratory infections.

4.2.4 Intake fraction as a basis for fate and exposure estimates

The location of air pollutant emissions in relation to exposed populations is a key factor influencing associated exposure and health risks (Evans et al. 2002; Levy et al. 2002; Marshall et al. 2003; Apte et al. 2012). Differences in proximate population density and local meteorology can produce substantial variability in the exposure consequences attributable to a given emissions source. Inhalation intake fraction (iF), which is defined as the ratio of mass of a pollutant inhaled by an exposed human population to the total mass associated with a given source (Bennett et al. 2002), provides a well-suited metric to consider $PM_{2.5}$ impacts in the context of LCIA.

$$iF = \frac{\text{Cumulative population inhalation intake (kg)}}{\text{Total pollutant emission (kg)}} \qquad (4.1)$$

iF accounts for the time and spatially integrated increase in concentration due to a life cycle inventory (LCI) emission, multiplied by intake rates. As an exposure metric, iF describes source-receptor relationships in a manner that allows for direct comparisons across emission sources and it can readily be related to potential toxicity in terms of specific health outcomes when exposure-response relationships are known (Fantke et al. 2015; Bennett et al. 2002; Ilacqua et al. 2007; Nazaroff 2008). The use of iF has become prevalent in exposure assessment studies both to characterize the magnitude of human exposure to a range of atmospheric contaminants and to express the variation in exposures that can result from specific sources of atmospheric emissions (Marshall et al. 2003; Apte et al. 2012; Bennett et al. 2002; Greco et al. 2007; Humbert et al. 2011; Tainio et al. 2009).

Reliable and consistent information on the relationship between emissions and exposure concentrations is needed to characterize intake fractions that are representative at any given spatial scale. Scales that need to be addressed include urban and rural outdoor environments as well as indoor environments with and without solid fuel combustion sources. Detailed and accurate data on emissions are often unavailable at the finer spatial scales that are needed to account for population heterogeneity across a large region. As an example of a study that addressed the heterogeneity among sources and receptor populations, Greco et al. (2007) quantified the United States county-level mobile source iF for primary $PM_{2.5}$ and separately for secondary $PM_{2.5}$ formed from NO_X and SO_2 emissions. They utilized source-receptor (S-R) matrices generated from the Climatological Regional Dispersion Model (CRDM). In a large study designed to address energy externalities by the US National Research Council (NRC National Research Council 2010a), the study team used the Air Pollution Emission Experiments and Policy Analysis (APEEP) model (Muller and Mendelsohn 2006) to develop iF relationships for primary and secondary $PM_{2.5}$ from ground level area sources, as well as from medium and high stack emissions from coal- and natural-gas fired power plants across the United States. Similar to Greco et al. (2007) APEEP used a county-level source-receptor matrix but with a different underlying modeling approach. Hodas et al. (2016) have recently provided a systematic assessment of iF values indoors for use in LCIA.

There are a number of factors that contribute globally to the variation of iF values for ambient emissions, in particular source characteristics, population density relative to source location, and meteorological conditions. Humbert et al. (2011) made a systematic evaluation of factors that impact iF for direct and secondary $PM_{2.5}$ health effects in LCIA and identified the following as key factors:

- Archetypes addressing variations in regions of emissions and exposure. For calculating iF for primary $PM_{2.5}$ emissions, a system of archetypes is needed at different aggregation levels that will provide a higher level of detail than can be achieved with currently available spatial models using a spatial resolution with 50 km square grids or larger. As shown by Lobscheid et al. (2012) and confirmed by Apte et al. (2012), there is a strong dependence of source distribution relative to population distribution such that the iF for primary $PM_{2.5}$ emissions from roadways and low stacks can be potentially underestimated without using high resolution (km scale or less) for emission to population exposure estimation to determine iF. This makes archetypes that can capture the variability of high resolution emission to population exposure maps essential for making reliable iF estimates for $PM_{2.5}$. A least four archetypal environments should be considered to account for outdoor sources in urban and rural or remote locations as well as indoor emissions from solid fuel combustion and other sources.
- Height of emission. Fate and exposure of PM is influenced by the emissions height. As an example, Levy et al. (2002) found that primary $PM_{2.5}$ intake fractions are at least four times greater for mobile (ground-level) emissions as for stationary source (elevated) emissions. There is therefore a need to further delineate outdoor emissions by emissions height according to emissions at ground-level, low-stack (~25 m), high-stack (~100 m), and very high stack (~250 m).
- Types of $PM_{2.5}$. In developing $PM_{2.5}$ iF, five species should be considered, namely direct emissions of primary $PM_{2.5}$ and formation of secondary $PM_{2.5}$ arising from emissions of the precursor substances SO_2, NO_x, NH_3 (as ammonium sulphate; ammonium nitrate), and volatile organic compounds (VOCs). The more variable component of secondary $PM_{2.5}$, particularly in urban environments, is the reaction of VOCs, originating from combustion processes and vegetation to form $PM_{2.5}$ through homogeneous nucleation, condensation, and oxidation reactions.

4.3 Description of indicator(s) selected

For calculating characterization factors (CF) for $PM_{2.5}$ health impacts, the general impact pathway is followed as described in Fantke et al. (2015), Humbert et al. (2015), and Humbert et al. (2011):

$$CF = \overbrace{(FF \times XF)}^{iF} \times ERF \times SF \qquad (4.2)$$

where the fate factor, FF [d], represents the multimedia transfer and loss processes in each compartment relating the emission rate [$kg_{emitted}$/d] to the steady-state mass in air [$kg_{in\ air}$]; the exposure factor, (XF [1/d], represents the daily fraction of air that is inhaled by the exposed population relating the mass in air [$kg_{in\ air}$] to the daily population intake dose [$kg_{inhaled}$/d]; the exposure-response slope factor, ERF [deaths/ $kg_{inhaled}$], represents the change in all-cause mortality (or other, specific disease endpoints) [deaths/d] per added population intake dose [$kg_{inhaled}$/d]; and the severity factor, SF [DALY/deaths], represents the change in human health damage expressed as disability-adjusted life years per death. At the impact indicator level, resulting CFs [deaths/$kg_{emitted}$] relate the change in mortality to emission rate and at damage indicator level, CFs [DALY/kgemitted] relate the change in damage to emission rate. The impact pathway followed is further detailed in the next section. We note that the iF is an integral measure of population exposure that does not account for individual variations of exposure within the population. It does however allow for assessing variations of exposure (and response) among different populations--that is from urban versus rural, among different cities, or among different urban regions. This variation is important in applying $PM_{2.5}$ exposure-response relationships that are non-linear for some health endpoints.

We selected a series of exposure metrics built around the nature and location of both indoor and outdoor primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursor emissions. The exposure metric chosen for all exposure scenarios is the human intake fraction (iF, product of FF and XF) expressed as the fraction of an emitted mass of $PM_{2.5}$ or precursor ultimately taken in as $PM_{2.5}$ by the total exposed population (Bennett et al. 2002). The intake fraction, which accounts directly for a temporally and spatially integrated concentration multiplied by nominal human intake rates, is a time- and space-integrated metric, easy to understand, to communicate, and to combine with chemical emissions (Fantke et al. 2015). Emission source types indoors and outdoors can be associated with a specific iF, which is easier to interface and combine at the level of human exposure than a field of indoor or ambient concentrations over a certain distance around the considered emission sources. The calculation of iF follows the general matrix approach outlined in the next section. Data for calculating iF for outdoor urban and outdoor rural environments are mainly based on Apte et al. (2012) and Brauer et al. (2016), respectively, while the basic ground work for calculating iF for different indoor source environments is provided by Hodas et al. (2016). Important for characterizing secondary $PM_{2.5}$ iF values are the factors used to convert precursors to $PM_{2.5}$ concentrations. These factors are discussed in more detail in the sections below.

We selected a series of health metrics building on the currently available global evidence for $PM_{2.5}$ summarized in the Global Burden of Disease (GBD) study series (Lim et al. 2012; Forouzanfar et al. 2015). The health metric chosen for exposure to $PM_{2.5}$ indoors and outdoors is the disability-adjusted life year (DALY) without age weighting and without discounting combining years of life lost (YLL) and years lived with a disability (YLD) weighted by the quality of life during the period of disability (Murray 1994). Basis for calculating DALY was chosen to be all-cause mortality expressed in deaths as basis for obtaining YLL based on current scientific evidence, whereas morbidity-related health effects from $PM_{2.5}$ show only negligible contribution to overall DALY (Apte et al. 2015).

If the ERF were simply linear, the slope would be constant and independent of variations of exposure among different population groups. But we must work with an ERF where the slope at low concentrations is substantially higher than the slope at high concentrations. To address this issue, we determine the ERF slope and the working point for exposure to $PM_{2.5}$ in indoor and outdoor environments based on the supralinear integrated risk function of Burnett et al. (2014) with data for outdoor background mortality rates based on Apte et al. (2015). The ERF and severity factors (DALY/death) are integrated into the general matrix approach.

Human health characterization factors quantify the source-to-total-mortality impacts of indoor and outdoor emissions of primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors as the number of early mortalities, with damages expressed in DALY per kgemitted. We build these impact indicators by integrating fate and exposure metrics with ERFs that have been established by the epidemiology community. The epidemiology research allows us to construct CFs that are disease-specific and location-specific with regard to background $PM_{2.5}$ exposures, and can then be summed up into a total impact or damage.

The overall $PM_{2.5}$ characterization framework includes four intermediate metrics and one damage metric. These are fate factors [d], exposure factors [1/d], intake fractions [$kg_{inhaled}/kg_{emitted}$], mortality as a function of intake in different archetypal environments [deaths/$kg_{emitted}$], and, as a damage category indicator, disability-adjusted life years lost attributable to $PM_{2.5}$ emissions [$DALY/kg_{emitted}$] in a variety of archetypal indoor and outdoor environments.

4.4 Model and method and specific issues addressed

4.4.1 Intake fractions

Ground level primary $PM_{2.5}$: Based on the above-discussed archetypes, we consider four main fate compartments for primary $PM_{2.5}$. This includes urban and rural outdoor environments and indoor environments with and without solid fuel combustion sources. The outdoor urban air compartment is parameterized according to Apte et al. (2012), providing city-specific population, area, and dilution rates for 3646 cities worldwide, considering by default a city of 240 km^2 and 2 million inhabitants (Humbert et al. 2011, Table 2). These data are used to calculate the rate constant by advection from urban to the rural continental region in which the considered city is embedded. The outdoor rural environment is parameterized based on the 17 subcontinental zones from USEtox 2.0 (Kounina et al. 2014), using an average overall deposition velocity of 418 m/d and considering by default the generic continent from USEtox with 9×1012 m^2 and 1 billion people. The indoor environments are parameterized according to Hodas et al. (2016) and Rosenbaum et al. (2015) for different regions of the world and are embedded within the urban and rural outdoor compartments. We first determine the K matrix of rate constants [1/d] characterizing removal and transfer rates within and between compartments. The rate constant for $PM_{2.5}$ infiltration from outdoor to indoor air is based on archetypical air exchange rates of 0.5 h^{-1} (for closed building envelopes) and 14 h^{-1} (for open buildings) combined with an average attenuation rate of 0.83 for closed building envelopes and no attenuation in open spaces with high ventilation rates. These values can be customized to a specific building type or region and to address uncertainty about issues such as how frequently high $PM_{2.5}$ emission cook stoves are used in closed or open buildings.

The matrix inverse of K provides the FF matrix of fate factors [d] of eq. 4.2. The chemical fate and resulting concentration and mass in each compartment account for all multiple inter-compartmental transfers between indoor and outdoor environments (see Hodas et al. 2016, Table 1, for further details) and between the urban and the rural regions. This makes it possible to assess for indoor and urban emission not only exposure within the considered city but also for the subsequent exposure occurring after transfer to the continental rural area, which may be especially relevant for small cities.

The XF matrix of exposure factors [1/d] is determined based on default indoor and outdoor breathing rates, the respective fraction of time spent indoor and outdoor and the volume and population in each of the above-described four compartments, characterizing the fraction of the air volume inhaled per day by the population in each compartment.

The intake fraction iF [$kg_{inhaled}/kg_{emitted}$] is then calculated as the product of these two 4 x 4 matrices FF and XF.

Influence of emission stack height: Compared with ground level emissions, high level stack emissions contribute to enhanced dilution of primary $PM_{2.5}$ and to reduced population exposure per unit mass emitted. This effect is accounted for multiplying the above-calculated intake fraction by urban- and rural-specific corrective factors that depend on the height of the considered stack. At this stage, we apply for primary $PM_{2.5}$ the same factors as those considered by Humbert et al. (2011, Table 3), which are derived from RiskPoll (Spadaro and Rabl 2012) and include correction factors of 0.34, 0.27 and 0.14 for low (~25 m), high (~100 m), and very high stacks (~250 m) in an urban environment (0.53, 0.44 and 0.35, respectively in a rural environment).

Secondary outdoor $PM_{2.5}$: A considerable fraction (up to 50%) of ambient $PM_{2.5}$ consists of sulphate, nitrate, and organic carbonaceous materials that have been formed by atmospheric chemistry from gaseous precursors, SO_2, NO_X, NH_3, and VOCs (Seinfeld and Pandis 2006). Most of the particulate-phase secondary inorganics in outdoor air are ammonium sulphate and ammonium nitrate formed from the reactions of $SO_2$and NO_X, originating from combustion of fuels for heat and power generation, transportation, and industry, with ammonia originating mostly from livestock, fertilizers and other agricultural chemicals (USEPA, 1998). The other, more variable part of secondary aerosols is formed from VOCs, originating from combustion processes and vegetation, formed through homogeneous nucleation (Kulmala and Kerminen 2008), condensation, and oxidation reactions. Intake fraction for secondary $PM_{2.5}$ is defined as the mass of inhaled secondary particulate matter, divided by the mass of the emitted gaseous precursor, e.g., sulphur dioxide or ammonia. Because two commonly found but independently released precursors are typically required in the formation of secondary $PM_{2.5}$ (the exception is homogeneous nucleation), and their reaction in the existing atmospheric concentration and temperature ranges are not rapid, secondary $PM_{2.5}$ formation may occur hundreds of kilometres away from the precursor emission sources. Near-field exposure therefore contributes less to the population iFs for secondary compared with the primary $PM_{2.5}$ and the elevation of the source above the ground level has a relatively small influence on the iFs for secondary $PM_{2.5}$.

There are a number of tools and databases available for assessing urban and regional scale iF for both primary and secondary $PM_{2.5}$. The Air Pollution Emission Experiments and Policy Analysis (APEEP) model addresses ground level and stack emissions in the USA at county-level scale (Muller and Mendelsohn 2006; NRC National Research Council 2010b). Zhou et al. (2006) calculated the iF values for the primary and secondary $PM_{2.5}$ from 29 high power plant stacks in China. The values are significantly higher than for similar power plants in the U.S., due in large part to the higher population density in China. Apte et al. (2012) compared local iF values for primary $PM_{2.5}$ from urban traffic and other dispersed ground level sources in 3646 cities with populations greater than 100 000 all over the world. Humbert et al. (2011) suggest a minimum set of default iF values for primary and secondary (nitrate and sulphate) $PM_{2.5}$ from ground, medium and high level emissions from urban, rural, and remote sources. Comparison of the data from different studies demonstrate (i) the impact of national population density on the iF from high stacks, (ii) the generally low iFs in the U.S. compared to most of the world, (iii) the apparent impact of ammonia emissions on secondary $PM_{2.5}$, and (iv) that the mean of population iFs of county level emissions is not an estimate of the population iF of the national emissions.

Different databases on iF values for secondary particles exist, i.e., APEEP (Apte et al. 2012; Humbert et al. 2011; Zhou et al. 2006), but they show rather large differences in iFs such that improved estimates for iFs are subject of currently on-going research. Improved iF estimates for secondary $PM_{2.5}$ from SO_2, NO_X, and NH_3 as well as from VOCs are presently being studied using models with more spatial and temporal resolution as part of a roadmap for further improvements (see Section 4.8e). It is nevertheless important that interim factors are provided for each of the main precursors. Since secondary $PM_{2.5}$ are transported over longer distances than primary $PM_{2.5}$, there is less difference between the urban and rural intake fractions than for primary $PM_{2.5}$. At this stage we propose to make use of the following interim iFs proposed by Humbert et al. (2011): for SO_2, secondary $PM_{2.5}$ intake fractions of 0.99 [$mg_{PM2.5\ inhaled}/kg_{SO2\ emitted}$] for emissions in urban areas and 0.79 [$mg_{PM2.5\ inhaled}/kg_{SO2\ emitted}$] in rural areas; for NO_X, iFs of 0.20 [$mg_{PM2.5\ inhaled}/kg_{NOx\ emitted}$] for emissions in urban areas and 0.17 [$mg_{PM2.5\ inhaled}/kg_{NOX\ emitted}$] in rural areas; and for NH_3, iFs of 1.7 [$mg_{PM2.5\ inhaled}/kg_{NH3\ emitted}$] for emissions in urban or rural areas. These will be updated once the results of the high-resolution, mass-balance models will be made available at world level.

Secondary indoor $PM_{2.5}$: Secondary organic aerosol (SOA) formed through chemical reactions involving reactive organic gases (ROGs) emitted indoors can constitute a significant fraction of domestic indoor $PM_{2.5}$ concentrations (Wainman et al. 2000; Waring and Siegel 2010; Waring et al. 2011; Waring and Siegel 2013; Waring 2014; Weschler and Shields 1999; Weschler 2006; Weschler 2011) and are potentially significant contributions to total intake of $PM_{2.5}$. Indoor sources of ROGs for which the calculation of SOA formation is likely to be of importance include cleaning products, cosmetics, air fresheners and other scented products, flame retardants, plasticizers, pesticides, building materials, paint, and furnishings (Bennett and Furtaw Jr. 2004; Gurunathan et al. 1998; Liang and Pankow 1996; Lioy 2006; Sarigiannis et al. 2011; Weschler and Nazaroff 2008). ROGs are also emitted by common indoor sources of $PM_{2.5}$ (e.g., tobacco smoke and solid fuel cook stoves); however, it is expected that measured $PM_{2.5}$ emissions factors for these sources capture emissions of both primary $PM_{2.5}$ and secondary $PM_{2.5}$ (i.e., SOA). As a result, the calculation of SOA derived from such sources is not required (nor recommended), as the calculation of SOA formation under these circumstances may lead to double counting of $PM_{2.5}$ emissions.

However, despite the large number of ROGs emitted indoors and the complexity of the chemical processes leading to SOA formation, potential health impacts associated with this source of $PM_{2.5}$ are currently not considered in the evaluation of product life cycle. Relevant products and services in this context are personal care products, cleaning products, building materials, and food preparation. Recent research has made substantial progress in modeling SOA formation indoors, and the framework for incorporating indoor SOA formation from indoor gas-phase emissions into LCIA is under development.

The SOA yield parameter (YSOA), which describes the ratio of the mass of SOA formed to the mass of ROG reacted, is an ideal descriptor of the $PM_{2.5}$-emission-equivalent associated with a given mass emission of an ROG. Further, the volatility basis set (VBS) approach for the calculation of YSOA, in which airborne organics are treated as a distribution of compounds binned by their volatilities Donahue et al. (2006), allows for the consideration of SOA formation from a wide range of organic compounds, while requiring a relatively small number of input parameters. There are now many emerging tools for calculating SOA emissions both for generic situations (Farina et al. 2010; Hodas et al. 2016; Lane et al. 2008; Waring 2014; Youssefi and Waring 2014) and product-specific situations (Bartzis et al. 2015; Haghighat and De Bellis 1998; Shin and Jo 2012). However, the review and aggregation of data describing additional input parameters representative of multiple indoor-environment archetypes and exposure scenarios is required before indoor SOA formation can be incorporated into LCIA. Factors for secondary indoor $PM_{2.5}$ will therefore be provided in a second stage of the work group effort.

4.4.2 Parameters influencing intake fractions

In developing the overall system for assessing cumulative intake of $PM_{2.5}$ emissions, and formation both outdoors and indoors, we compiled and evaluated parameters separately with regard to their influence on intake fraction values for $PM_{2.5}$ of outdoor and indoor origin.

The following parameters have a predominant influence on iF for $PM_{2.5}$ of outdoor origin:

- Linear population density [LPD]: iF is linearly proportional to LPD, i.e., the value of iF is increased in direct proportion to the increase of the exposed population.
- Breathing rate [BR]: iF is linearly proportional to BR, which varies temporally and between individuals, but the long term BR variation between populations is negligible.
- Wind speed [u]: iF is inversely proportional to the areal average wind speed.
- Mixing height [h]: For ground level sources iF is inversely proportional to the mixing height. For high stack sources the relation is more complicated. When mixing height is low, i.e., vertical mixing is small, high stack emissions are poorly mixed to ground level in the vicinity of the source, and, consequently, the overall iF is significantly reduced. In effect high stack protects the population in the vicinity of the source from the emissions, and this protection zone – and respectively the protected population – increases as the mixing height decreases. Consequently, the iF impact of the high stack depends on the local topography, meteorology, and population distribution relative to the emission source location. For low stack sources the situation lies between the ground level and high stack sources, but closer to the former.
- Source to recipient distance [s]: Assuming uniform distribution of wind direction, the long term average iFi [individual intake fraction] is in principle inversely proportional to the square of source to receptor distance. This is relevant for a population iF if it is summed up from iF values.
- Infiltration: The indoor concentration of $PM_{2.5}$ of outdoor origin is attenuated relative to the respective concentration in outdoor air due to (i) incomplete penetration through leaks in the building envelope, (ii) active filtration either of intake air in the ventilation system and/or indoor air by a stand-alone air cleaner, and (iii) deposition within the room. This attenuation ranges from 0 to 90%, and as populations spend 80 – 90% of time indoors, it may significantly reduce the iF.
- Time-microenvironment-activity: The proportion of time spent in indoor environments is, in principle, relevant for the value of iF, but as it varies only little between populations it does not introduce significant variation into population iF's.

Since indoor iF equals the amount of air breathed in an indoor space divided by the amount of air exchanged to and from this space, the following parameters have a predominant influence on iF for $PM_{2.5}$ of indoor origin (Hodas et al. 2016):

- Building air exchange rate [k_{ACH}]: The value of iF is almost inversely proportional to air exchange rate. Almost – because reducing the air exchange rate for a room [one particle removal mechanism] can slightly increase deposition [another particle removal mechanism] in that room due a longer residence time making particles more susceptible to deposition.
- Building volume: This parameter influences dilution of particle emissions, as well as occupancy density.
- Inter- and intra-zonal air flows and mixing: Airflow within a room or within a building zone can influence the uniformity of dispersion of $PM_{2.5}$ in the indoor environment and exposures for varying source-to-recipient distances. A single-zone, well-mixed indoor environment approximation is commonly assumed.
- $PM_{2.5}$ removal mechanisms: Key mechanisms by which particles are removed from indoor air are deposition to surfaces and filtration in Heating Ventilation and Air Conditioning (HVAC) systems that recirculate air. Removal by filtration is dependent on the prevalence of mechanical ventilation systems, HVAC-system air recirculation rates, and the fraction of indoor air that passes through HVAC systems.
- Breathing rate: See parameters influencing iF of outdoor origin.
- Person-hours per day: See Time-microenvironment-activity described in parameters influencing iF of outdoor origin. iF is directly proportional to the number of individuals and the time they spend in the room.

The reference state in the $PM_{2.5}$ life cycle impact assessment is the current local condition in the given location, including emissions, air quality, built infrastructure, population level and demographics, socioeconomics, and morbidity and mortality.

4.4.3 Archetypes

For calculating the intake fractions (iF) for primary $PM_{2.5}$ emissions, we propose a system of archetypes at different aggregation levels that will provide a higher level of detail than can be achieved with currently available spatial models at 50 times 50 km level. We first consider an outdoor archetype, differentiated into urban and rural or remote areas, which are further divided into ground level, low stack, high stack, and very high stack emissions. Default values are provided at world level for a TIER 1 iF calculation (Table 4.1). In TIER 2 the urban archetype is divided into small, medium, and large cities, and in TIER 3 the actual population and outdoor and indoor environment characteristics of each of 3646 cities are used in the iF calculation.

For calculating iFs for indoor sources of primary $PM_{2.5}$, the indoor archetypes for low (no solid fuel combustion-related sources) and high (solid fuel combustion sources) background concentrations are differentiated according to air exchange rate between high, medium, and low ventilation rate, which are further subdivided into with and without $PM_{2.5}$ filtration, and into indoor spaces with high and low occupancy. TIER 1 provides default values for these low and high (background concentration) archetypes at world level. TIER 2 adds more detailed input parameters such as filtration efficiency and indoor air recirculation, and TIER 3 incorporates actual local data for residential and occupational indoor environments and occupancy levels. For each region or area (e.g., Indochina, Scandinavia), the iF is weighted according to the proportion of the contribution of this region to the total emission in the considered geographical domain (typically continental or global scale). The application or potential refinement or extension of the archetype structure to the formation of secondary $PM_{2.5}$ from the emission and/or formation of precursors (NO_X, SO_2, NH_3, VOCs) will be addressed in a second stage.

4.4.4 Exposure-response

For use in life cycle impact assessment, it would be ideal to have concentration-response functions that reflected the impacts of both short-term and chronic exposure to $PM_{2.5}$. In many previous studies it has been shown that the effect estimates from the cohort studies are approximately an order of magnitude larger than those derived from time-series studies. As a result, many analysts estimate the mortality impacts of $PM_{2.5}$ exposure for policy analysis using only the cohort results – with the understanding that these estimates serve as a good proxy for the combined impact of short-term and chronic effects. Such an approach has been adopted in the 2010 Global Burden of Disease analysis (Lim et al. 2012). For use in life cycle impact assessment, it is necessary to have concentration-response functions that cover the full range of annual average concentrations seen in the ambient environment. The cohort studies that have been reported to date typically involve ambient annual mean concentrations in the range of 5 to 30 $\mu g/m^3$. Until recently this posed a problem for the application of these results in LCIA because in many parts of the world ambient concentrations may be well above these levels, reaching values as high as ~100 $\mu g/m^3$.

We use the integrated exposure-response (IER) function, developed by Burnett et al. (2014) to support the 2010 GBD analysis. The IER function is of the form $RR = 1 + \alpha\,(1 - \exp(-\beta\,(C - Co)^{\rho}))$, where RR is the relative risk (i.e., the mortality rate among those exposed to concentration C divided by the mortality rate among those exposed to the counterfactual concentration, Co); α is the asymptotic increase in relative risk as the concentration goes to infinity; and β and ρ are coefficients which describe the rate of increase of risk as concentrations rise from the counterfactual level, Co. Burnett et al. (2014) estimated the IER coefficients α, β, ρ and Co by fitting their equation to the results from the 8 cohort studies of ambient PM air pollution, as well as to the data on relative risks seen at the fine PM exposures characteristic of second hand smoke, indoor cooking with solid fuels and heating, and active smoking. In this way, Burnett et al. (2014) obtained a set of 1000 equally likely possible sets of values for the four empirical coefficients and exposure-response functions for each disease of interest. The IER assumes that fine particle mass concentration is an adequate proxy for toxicity, without regard to the origin or composition of the particles. In spite of the availability of an IER that can address both indoor and outdoor sources in a similar framework (Burnett et al. 2014), it is clear that significant challenges remain in differentiating effects of indoor and outdoor sources. Our model is designed in a way that characterization factors for LCIA are based on this IER function because it represents a widely-scrutinized synthesis of estimates and because it allows estimation of risk at the levels of exposure (well above 30 $\mu g/m^3$) currently found in many urban areas of the world.

The mortality attributable to a specified level of chronic exposure to ambient fine particulate matter, C (µg/m^3), is estimated by multiplying the total number of deaths due to the disease in the year of interest, M (deaths), by the attributable risk fraction, ARF – which itself is simply (RR – 1) / RR. The attributable risk fraction inherently compares the relative risk at the current concentration, C, with the relative risk at a counterfactual concentration, Co. The counterfactual is defined, in the burden of disease studies, as an optimal level of exposure corresponding to the theoretical minimum risk (Lim et al. 2012). Since current epidemiological research has not identified a threshold for $PM_{2.5}$ (i.e., a concentration below which no adverse health effects are observed) the minimum pollutant concentrations at which health effects have been observed have been used as counterfactuals (Cohen et al. 2005; Pope et al. 2002). For $PM_{2.5}$ effects have been seen down to concentrations in the range of 5.8 – 8.8 µg/m^3 (Lim et al. 2012).

To implement the approach, it is necessary to obtain data on mortality rates for each of the five causes of death – among adults (ischemic heart disease, stroke, chronic obstructive pulmonary disease, and cancers of the trachea, bronchus, and lung) and among young children (acute lower respiratory infections) – considered by the IER (Lim et al. 2012). The 2010 data on mortality rates for each country and region of the world used to support the 2010 GBD analysis are available from the Institute for Health Metrics and Evaluation. These data are age, sex, and disease specific and have already been corrected to account for country-to-country variations in the reporting of certain causes of death (the so-called "garbage codes"). The IHME data for 2010 are used in our model to support the development of characterization factors for use in LCIA.

There is uncertainty in estimates of the relative risks, and therefore the attributable risk fractions, derived using the IER. As noted above Burnett et al. (2014) included uncertainty in their estimates of the four IER parameters, and have made their work available for use by others. Burnett's estimates of the parameter uncertainty in the IER can readily be used in LCIA to provide a sense of the minimum possible uncertainty in results derived using this approach. We note however, that substantially larger epistemic uncertainties are inherent in the approach because it relies on the assumption that particles from all sources – autos, power plants, road dust, cook stoves, passive cigarette smoke – are equivalently toxic on a unit mass basis. In addition, the approach assumes that relative risks derived from a meta-analysis of cohort studies, in which the numerical results are dominated by estimates from studies conducted in the US can be transferred to estimate risks in other populations. Clearly, these two assumptions introduce potentially substantial uncertainties which have not as yet been quantitatively characterized and are not reflected in the parameter uncertainty values derived by Burnett et al. (2014).

If the exposure-response function were linear, the slope would be constant and independent of the current level of exposure. However, as seen above, the integrated exposure response function is not linear – the slope at low concentrations is substantially higher than the slope at high concentrations. This implies that characterization factors for $PM_{2.5}$ will not be constant, but will depend on the current level of exposure in the city or region in which emissions changes will occur. Furthermore, there is a question of which slope should be used in LCIA – the local marginal slope of the concentration-response function or the average slope of the concentration-response function over the region between the current level of exposure, C, and the counterfactual level of exposure, C_o. We note that it is not obvious in all circumstances how to characterize the relevant level of exposure, C. For exposure to pollutants of outdoor origin, it seems relatively clear that the ambient outdoor concentration is the relevant "working level." Similarly, it seems likely that the indoor $PM_{2.5}$ concentration in homes using cook stoves and dirty fuels is the relevant "working level." What to do in other situations – for instance when evaluating indoor particulate emissions from other sources in homes in the US/Europe without such cook stoves – is less clear. Our model is constructed in a way that for consequential LCIA the marginal slope can be used and that for attributional LCIA the average slope between the working point and the minimum risk can be used.

4.5 Characterization factors

Characterization factors (CFs) representing human health impacts from exposure to $PM_{2.5}$ due to emissions of primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors indoors (with and without solid fuel combustion sources) and outdoors (in urban and rural environments) are provided at impact and damage levels. At impact level, CFs are expressed as change in disease incidences per kg emissions of $PM_{2.5}$ or precursors [deaths/$kg_{emitted}$] for premature all-cause mortality (recommended health endpoint) or other individual disease endpoints (premature mortality for adults, age≥25, from ischemic heart disease [IHD]; cerebrovascular disease [stroke]; chronic obstructive pulmonary disease [COPD]; and lung cancer [LC]; and for children, age<5, acute respiratory lung infection [ALRI]). At damage level, CFs are expressed as change in disability-adjusted life years per kg emissions of $PM_{2.5}$ or precursors [DALY/$kg_{emitted}$]. CFs are thereby interpreted as additional mortality or DALY over background or base line level per kg additional primary $PM_{2.5}$ or secondary $PM_{2.5}$ precursor emitted. These characterization factors are available for download from the Life Cycle Initiative's website (http://www.lifecycleinitiative.org/applying-lca/lcia-cf).

4.5.1 Preliminary characterization factors

A preliminary set of intake fractions and characterization factors for human health effects associated with exposure to $PM_{2.5}$ from emissions of primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors in urban and rural outdoor environments and low and high background concentration indoor environments is provided in Table 4.1 and Table 4.2. Factors listed in Table 4.1 were calculated using the marginal slope at the background concentration working point on the ERF for total mortality due to $PM_{2.5}$ exposure, whereas factors listed in Table 4.2 were derived considering the average between the background concentration working point on the ERF and the theoretical minimum-risk level of 5.8 µg/m^3 for total mortality due to $PM_{2.5}$ exposure. This set of intake fractions and characterization factors will be further evaluated and refined particularly for indoor emission

Table 4.1: Summary of preliminary intake fractions (kg intake per kg emitted), and characterization factors at midpoint (deaths per kg emitted) and endpoint (disability-adjusted life years per kg emitted) for primary $PM_{2.5}$ emissions and for secondary $PM_{2.5}$ precursor emissions applying the marginal slope at the ERF working point.

Pollutant	Emission compartment	Emission source type	kg intake/ kg emitted	Death/ kg emitted	DALY/ kg emitted
$PM_{2.5}$	Outdoor urban	Ground level (RES)+	3.6×10^{-05}	1.6×10^{-04}	3.4×10^{-03}
		Low stack	1.2×10^{-05}	5.8×10^{-05}	1.2×10^{-03}
		High stack	9.5×10^{-06}	4.5×10^{-05}	9.1×10^{-04}
		Very high stack	5.2×10^{-06}	2.4×10^{-05}	4.9×10^{-04}
	Outdoor rural	Ground level	6.3×10^{-06}	4.8×10^{-06}	9.8×10^{-05}
		Low stack	2.2×10^{-06}	1.7×10^{-06}	3.4×10^{-05}
		High stack	1.7×10^{-06}	1.3×10^{-06}	2.6×10^{-05}
		Very high stack	9.1×10^{-07}	6.9×10^{-07}	1.4×10^{-05}
	Indoor low*	No solid fuel cooking	1.5×10^{-02}	8.3×10^{-02}	$1.7\times10^{+00}$
	Indoor high*	Solid fuel cooking	6.4×10^{-04}	2.5×10^{-04}	5.1×10^{-03}
NO_x	Outdoor urban	–	2.0×10^{-07}	1.3×10^{-06}	2.5×10^{-05}
	Outdoor rural	–	1.7×10^{-07}	7.4×10^{-08}	1.4×10^{-06}
	Indoor low*	–	2.0×10^{-07}	1.2×10^{-06}	2.3×10^{-05}
	Indoor high*	–	1.7×10^{-07}	1.8×10^{-06}	3.3×10^{-05}
SO_2	Outdoor urban	–	9.9×10^{-07}	6.6×10^{-06}	1.3×10^{-04}
	Outdoor rural	–	7.9×10^{-07}	3.4×10^{-07}	6.5×10^{-06}
	Indoor low*	–	9.9×10^{-07}	5.9×10^{-06}	1.1×10^{-04}
	Indoor high*	–	7.9×10^{-07}	8.2×10^{-06}	1.5×10^{-04}
NH_3	Outdoor urban	–	1.7×10^{-06}	1.1×10^{-05}	2.2×10^{-04}
	Outdoor rural	–	1.7×10^{-06}	7.4×10^{-07}	1.4×10^{-05}
	Indoor low*	–	1.7×10^{-06}	1.0×10^{-05}	1.9×10^{-04}
	Indoor high*	–	1.7×10^{-06}	1.8×10^{-05}	3.3×10^{-04}

+ RES: reference emissions scenario

*Low and high refers to the considered background concentration taken as working point and (indoors) typically corresponding to low and high air exchange rates.

sources and for the formation of secondary $PM_{2.5}$ from precursor emissions outdoors and indoors to arrive at a fully recommended set of factors for use in LCIA. Intake fractions and characterization factors are all situation-specific. Both the substance and the scenario should be specified in the case where a reference situation is required, e.g., $PM_{2.5}$ outdoor urban ground-level emissions. Currently, there is no agreement on a reference emission scenario (RES) for $PM_{2.5}$. If practitioners need to choose a reference $PM_{2.5}$ emission scenario and report characterization factors for emissions given in kg $PM_{2.5}$-equivalents, we recommend to refer to 1 kg $PM_{2.5}$ for the global outdoor urban (population-weighted average across 3646 cities with more than 100,000 inhabitants) ground-level emission archetype, noting that characterization factors for $PM_{2.5}$ vary with location and time. This reference scenario corresponds to the first entry in Table 4.1 where this entry is identified as the RES.

4.5.2 Uncertainty and variability

Uncertainty, variability, and significance are concepts previously discussed in the context of human health impact assessment in LCIA, both between impact categories and within a category (Barnthouse et al. 1997). It is noted that the comparative nature of life cycle assessment (LCA) makes it especially important to include these considerations. However, much of the prior recommendation language regarding these three concepts is in the construct of LCIA generally or modeling fate, exposure, and effects, but not specifically for particulate matter. Previously available multi-parameter air quality models have also been noted as lacking in their ability to handle secondary aerosols, thought to be potentially significant contributors, thus underestimating toxicity in some situations (Udo de Haes et al. 2002).

Table 4.2. Summary of preliminary intake fractions (kg intake per kg emitted), and characterization factors at midpoint (deaths per kg emitted) and endpoint (disability-adjusted life years per kg emitted) for primary $PM_{2.5}$ emissions and for secondary $PM_{2.5}$ precursor emissions applying the average slope between the ERF working point and the theoretical minimum-risk level.

Pollutant	Emission compartment	Emission source type	kg intake/ kg emitted	Death/ kg emitted	DALY/ kg emitted
$PM_{2.5}$	Outdoor urban	Ground level	3.6×10^{-05}	2.4×10^{-04}	4.9×10^{-03}
		Low stack	1.2×10^{-05}	8.2×10^{-05}	1.7×10^{-03}
		High stack	9.5×10^{-06}	6.3×10^{-05}	1.3×10^{-03}
		Very high stack	5.2×10^{-06}	3.4×10^{-05}	7.0×10^{-04}
	Outdoor rural	Ground level	6.3×10^{-06}	1.1×10^{-05}	2.3×10^{-04}
		Low stack	2.2×10^{-06}	3.9×10^{-06}	8.0×10^{-05}
		High stack	1.7×10^{-06}	3.0×10^{-06}	6.2×10^{-05}
		Very high stack	9.1×10^{-07}	1.6×10^{-06}	3.3×10^{-05}
	Indoor low*	–	1.5×10^{-02}	1.1×10^{-01}	$2.3\times10^{+00}$
	Indoor high*	–	6.3×10^{-04}	8.2×10^{-04}	1.7×10^{-02}
NO_X	Outdoor urban	–	2.0×10^{-07}	1.6×10^{-06}	3.1×10^{-05}
	Outdoor rural	–	1.7×10^{-07}	2.1×10^{-07}	4.0×10^{-06}
	Indoor low*	–	2.0×10^{-07}	1.5×10^{-06}	2.8×10^{-05}
	Indoor high*	–	1.7×10^{-07}	1.2×10^{-06}	2.3×10^{-05}
SO_2	Outdoor urban	–	9.9×10^{-07}	8.0×10^{-06}	1.5×10^{-04}
	Outdoor rural	–	7.9×10^{-07}	9.9×10^{-07}	1.9×10^{-05}
	Indoor low*	–	9.9×10^{-07}	7.2×10^{-06}	1.4×10^{-04}
	Indoor high*	–	7.9×10^{-07}	5.6×10^{-06}	1.1×10^{-04}
NH_3	Outdoor urban	–	1.7×10^{-06}	1.4×10^{-05}	2.6×10^{-04}
	Outdoor rural	–	1.7×10^{-06}	2.1×10^{-05}	4.0×10^{-05}
	Indoor low*	–	1.7×10^{-06}	1.2×10^{-05}	2.3×10^{-04}
	Indoor high*	–	1.7×10^{-06}	1.2×10^{-05}	2.3×10^{-04}

*Low and high refers to the considered background concentration taken as working point.

Uncertainty is a combination of errors in the likelihood estimator of a data distribution and in model specification at the parameter and model construct levels, also referred to as technical uncertainty (Funtowicz and Ravetz 1990). Output variability is the propagation of empirical values distributed across real ranges of inputs to the dependent parameter. These distributions result in frequency plots while uncertainty is typically characterized in probability distributions.

The most fundamental expression of the proposed $PM_{2.5}$ model conforms to the traditional combination of LCI and LCIA results to human health-related annual impact scores, IS [DALY/FU] as IS = CF × m, where CF [DALY/$kg_{emitted}$] is the characterization factor and m [$kg_{emitted}$/FU] is the emission mass per functional unit (actually emission mass or flow vector) from the inventory analysis (Fantke et al. 2015).

Sources of uncertainty in the current model (including direct supporting data):

- Data uncertainties – robustness (how much, how good) and relevancy (how appropriate – interpolations and extrapolations, background concentrations)
- Parameter uncertainties – resolution of the ERF curves – generic versus specific
- Model uncertainties – fate and exposure components, ERF slope factor selection, population placement on ERF curves.

Building on the archetype structure applied for characterizing emissions of primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors, inter-urban variability will be included in the uncertainty estimates around calculated characterization factors as shown in Figure 4.2, where with increasing level of aggregation, uncertainty also increases due to unaccounted for variability. Uncertainty is further discussed in Chapter 2 (crosscutting issues).

4.6 Rice case study application

To evaluate the presented $PM_{2.5}$ modeling framework in an LCA application context, emissions were quantified for a common rice production and processing case study that was developed as described in Frischknecht et al. (2016). The emitted masses of primary $PM_{2.5}$ and precursor substances NH_3, NO_X, and SO_2 to secondary $PM_{2.5}$ are summarized in Figure 4.3 for three distinct scenarios. The first scenario of rice production and processing in rural USA and distribution and cooking in urban Switzerland yielded predominantly outdoor air emissions of $PM_{2.5}$ and precursors mainly attributable to rice

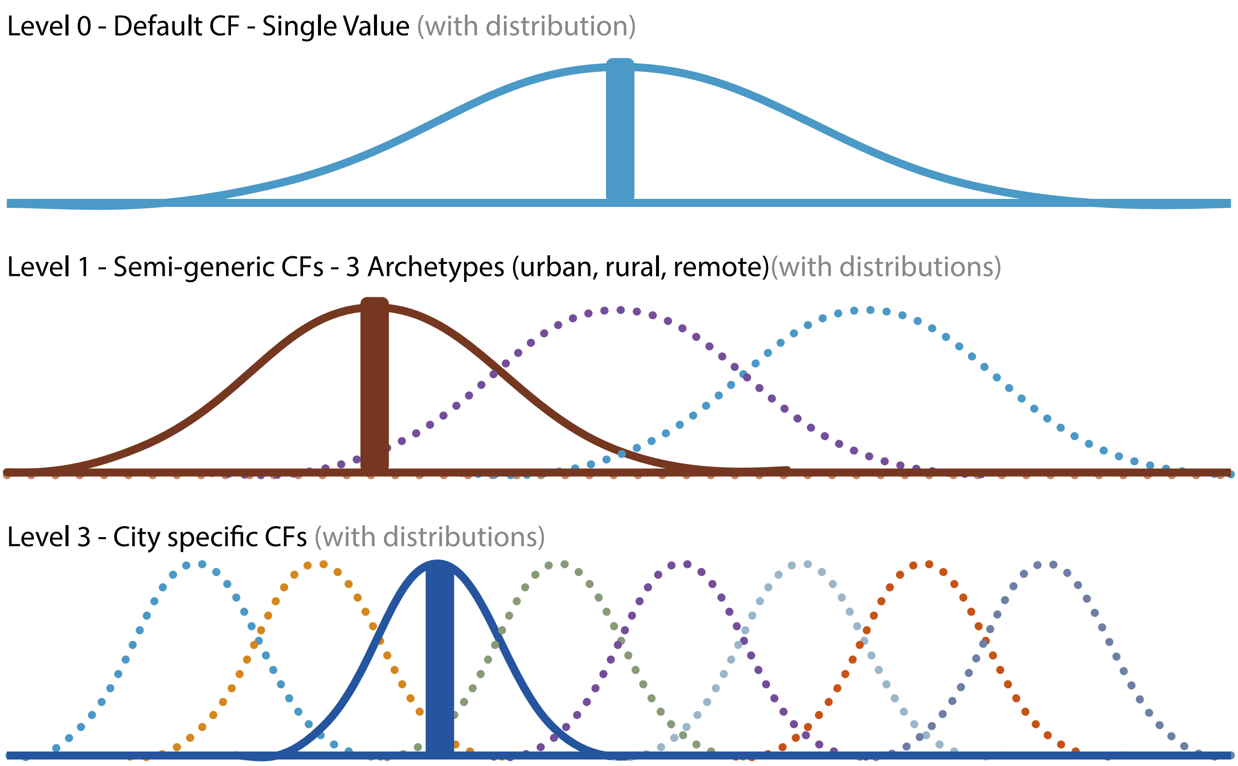

Figure 4.2: Conceptual illustration of considering uncertainty due to variability in characterization factors (CFs) as function of level of archetypal aggregation.

production in rural USA (due to burning of rice fields after harvest) and transport from USA to Switzerland, whereas only a small amount of $PM_{2.5}$ and precursors is emitted indoors from using a gas stove for cooking rice (low indoor background concentrations). The second scenario of rice production and processing in rural China and distribution and cooking in urban China yielded only outdoor emissions associated with production (assuming rice fields are burned after harvest) and processing in rural areas, and with electric rice cooker use in urban areas due to electricity predominantly generated from coal. The third scenario of rice production, processing, distribution, and cooking in rural India yielded predominantly indoor emissions in rural areas with high background concentrations from cooking rice using wood stoves (solid fuel combustion) as well as outdoor emissions from production, processing, and transport in rural areas.

Background concentrations for $PM_{2.5}$ and precursors in rural outdoor air and corresponding background mortality rates have been applied from Brauer et al. (2016) and Apte et al. (2015), respectively, for rice production in the state of Arkansas (USA), province of Hunan (China), and the state of West Bengal (India). Background concentrations for $PM_{2.5}$ and precursors in urban outdoor air have been applied from Apte et al. (2012) and corresponding background mortality rates (extrapolation from one of the regions used in Apte et al. (2015) to individual cities) for rice consumption in Geneva (Switzerland), Shanghai (China), and Kolkata (India). Intake fractions for all emission compartments and scenarios are shown in Figure 4.4, where city-specific data yield different intake fractions for outdoor urban air. Highest iF values are found for $PM_{2.5}$ in indoor air with low background concentration (without solid fuel combustion sources) for a closed building followed by indoor air with high background concentration for a well ventilated building, outdoor urban air, and finally outdoor rural air. In all emission compartments except outdoor rural air, emissions of secondary $PM_{2.5}$ precursors are negligible compared with emissions of primary $PM_{2.5}$. In outdoor rural air, iF from emissions of NH_3 and SO_2 are almost in the same range as iF from emissions of primary $PM_{2.5}$.

Exposure-response curves are combined with intake fractions to yield characterization factors and further combined with emissions from the three different rice productions and processing scenarios to finally yield damages on human health from exposure to $PM_{2.5}$ expressed in DALY per functional unit, i.e., DALY per kg cooked white rice Figure 4.5. Two different approaches for the ERF slope have been tested, namely the marginal slope at the background concentration working point on the ERF curve (Figure 4.5a) and the average between the background concentration working point on the ERF curve and the theoretical minimum-risk level of 5.8 µg/m³ (Figure 4.5b).

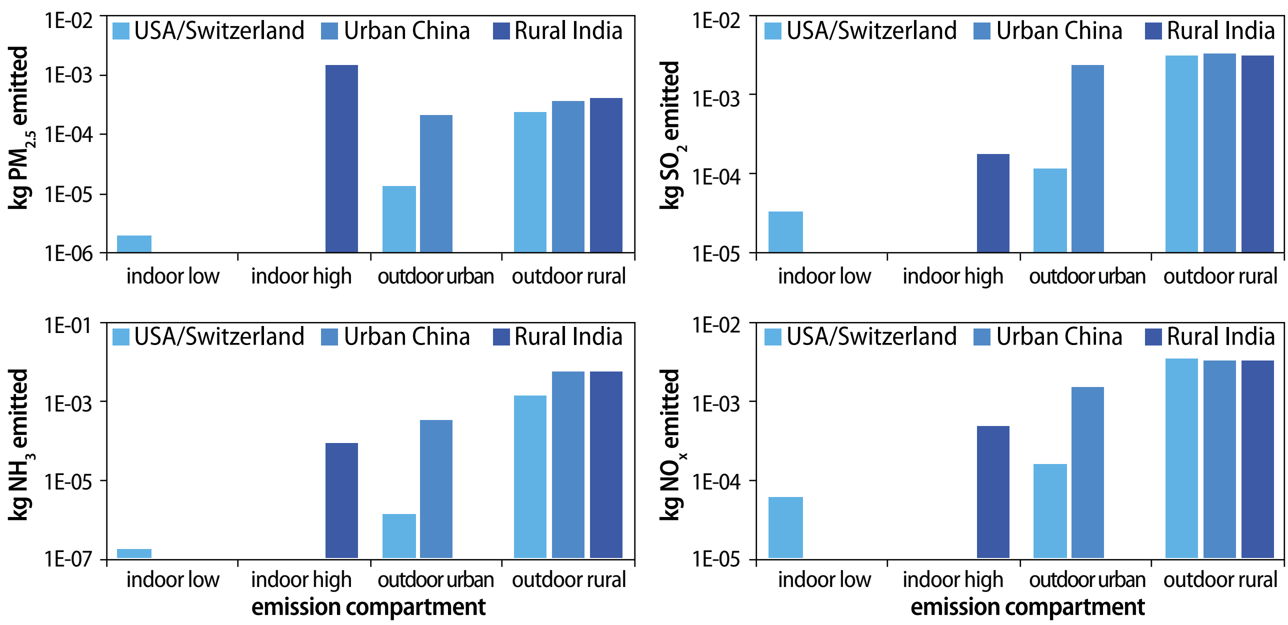

Figure 4.3: Emitted mass [kg] of fine particulate matter ($PM_{2.5}$), and precursors to secondary particles, i.e., SO_2, NH_3, and NO_x, per kilogram of cooked rice in the three scenarios USA/Switzerland (rice production and processing in rural USA and distribution and cooking in urban Switzerland), urban China (rice production and processing in rural China and distribution, and cooking in urban China), and rural India (rice production, processing, distribution and cooking in rural India).

The marginal approach ideally takes the current situation as the working point (in our case, we applied the actual background concentrations of the different scenarios) and is most appropriate when informing decisions that affect short-term and restricted changes in overall emissions occur, while the average approach may be relevant when larger and longer term changes are expected due to human interventions over the lifetime of the considered product or infrastructure necessary to its production. Differences between these two approaches are relatively small in absolute measures (DALY). In constrast, the difference in the slope between both approaches influences more the contribution of secondary $PM_{2.5}$ precursors to the overall impacts with a maximum difference of 14% for the contribution of secondary $PM_{2.5}$ to the emissions to outdoor urban air in the urban China scenario as function of the use of different ERF slopes. Overall, highest impacts are estimated for indoor air of rural India, mainly attributable to indoor cooking with wood stoves (solid fuel combustion) and in indoor air of urban Switzerland (with low background concentration), mainly due to gas stove-related $PM_{2.5}$ emissions.

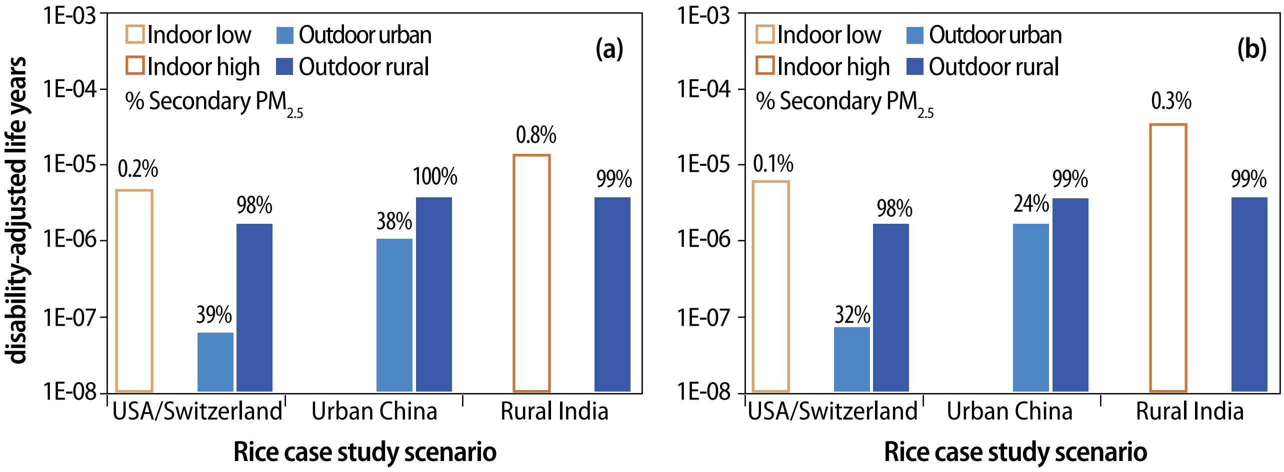

Figure 4.5: Disability-adjusted life years taking (a) the marginal slope at the working point, and (b) the average from the working point to the theoretical minimum-risk per kilogram of cooked rice (DALY) and percent contribution of total secondary $PM_{2.5}$ precursor emissions (%) in the three scenarios USA/Switzerland (rice production and processing in rural USA and distribution and cooking in urban Switzerland), urban China (rice production and processing in rural China and distribution and cooking in urban China), and rural India (rice production, processing, distribution, and cooking in rural India).

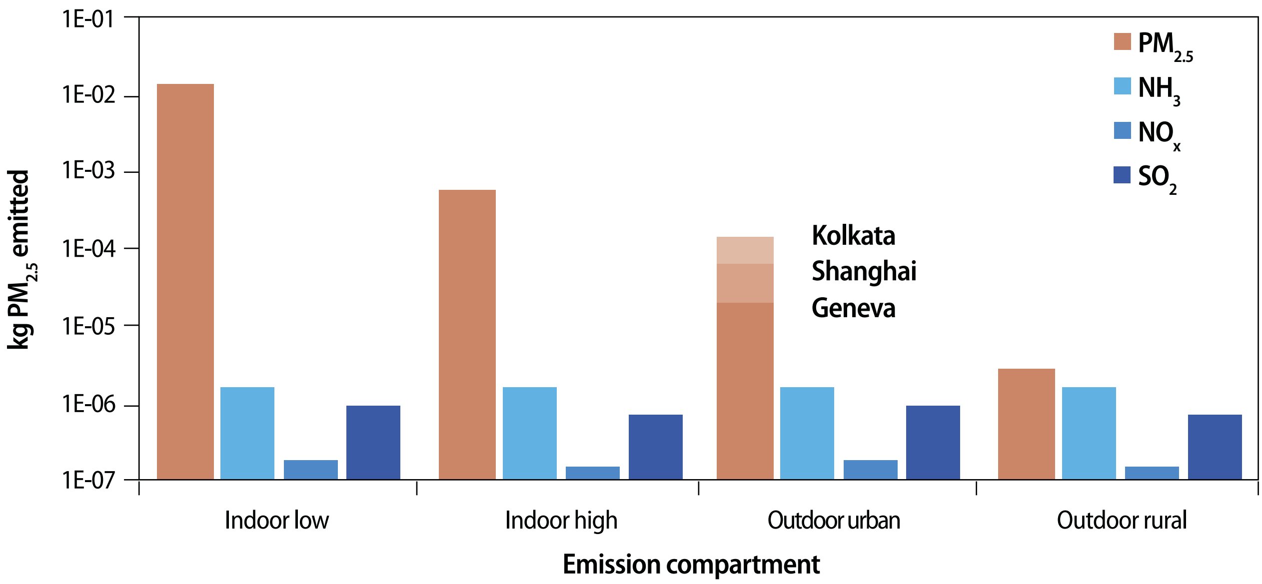

Figure 4.4: Intake fraction [$kg_{inhaled}/kg_{emitted}$] indicating kg $PM_{2.5}$ inhaled per kg $PM_{2.5}$ emitted for primary $PM_{2.5}$, and kg $PM_{2.5}$ inhaled per kg precursor emitted for secondary $PM_{2.5}$. Precursor SO_2, NO_x, and NH_3 contribute to secondary $PM_{2.5}$ formation outdoors via ammonium nitrate and ammonium sulphate.

This emphasizes the importance of including indoor sources and exposure for health impacts associated with $PM_{2.5}$. Impacts in outdoor air mainly occur in the rural environment, which is due to the rice production contributing largely to outdoor primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursor emissions. This emphasizes the importance of distinguishing between rural and urban areas in outdoor air, which is best done in an approach based on archetypes, where city-specific differences can be accounted for.

4.7 Recommendations and outlook

4.7.1 Main recommendation – Short summary

The main recommendation for this chapter involves both the process for linking emissions to exposure and the process for linking exposure to disease and mortality. The overall structure of our recommendation for characterizing the impacts of $PM_{2.5}$ exposures are organized according outdoor and indoor emissions, urban and rural regions, primary and secondary $PM_{2.5}$ exposures and ground level versus stack emissions. Table 4.3 summarizes recommendations for outdoor air emissions characterization factors as a matrix characterization factors for primary or secondary $PM_{2.5}$, urban or rural emissions, ground level or stack emissions. Table 4.4 summarizes recommendations for indoor air emissions characterization factors as a matrix characterization factors for primary or secondary $PM_{2.5}$, for the level of ventilation and for background exposures. The guidance for the set of characterization factors that result are described in terms of being "strong recommendations," "recommendations," or "interim recommendations."

For both outdoor and indoor emissions, the intake fraction approach based on mass-balance modeling for direct $PM_{2.5}$ and precursors to secondary $PM_{2.5}$ emissions provides a useful and well-documented approach for linking inventories to exposures. Secondary $PM_{2.5}$ formations can be addressed both indoors and outdoors with archetypal models currently available in the literature for provisional characterization factors. In the near future we expect the availability for LCA of models with more spatial and temporal resolution for capturing secondary $PM_{2.5}$ formation in ambient air. Well-vetted, exposure-response models are available for assessing both total mortality and disease specific DALYs associated with $PM_{2.5}$ exposures both indoors and outdoors. Proper application of these models to LCIA requires that background exposure to $PM_{2.5}$, as well as background disease incidence (and/or mortality) be included in the calculation of impacts for any selected population.

Table 4.3: Matrix of recommendations for characterization factors for outdoor emissions of $PM_{2.5}$ and secondary $PM_{2.5}$ precursors.

	Urban	Rural		
	Ground level	Stack	Ground level	Stack
Primary $PM_{2.5}$	Recommended factors with **city specific intake fractions** and exposure response functions • Global default based on city distributions adapted from Apte et al. (2012) and Apte et al. (2015) • Factors will be strongly recommended once robustness tests are performed and paper published	Interim recommended **generic factors for very high, high, and low stack** based on ground level and correction factors from Humbert et al. (2011) • Factors will be recommended based on updating latest available iF from point sources for high stack emissions	Recommended factors for rural archetype from multi-compartmental indoor-outdoor model • **Global default** with distributions • **Regional defaults** with distributions for the USEtox regions	
Secondary $PM_{2.5}$	• **Interim recommended factors** for urban and rural archetypes based on intake fractions for secondary $PM_{2.5}$ precursors (Humbert et al. 2011) and same ERFs as for ground level primary $PM_{2.5}$ • A **roadmap** has been established for updating secondary PM^2.5 characterization factors, based on spatially explicit models			

4.7.2 Judgment on quality, interim versus recommended status of the factors and recommendations

For outdoor emissions at ground level in urban areas we recommend characterization factors for primary $PM_{2.5}$ that have city specific intake fractions along with exposure response functions taken from Apte et al. (2012) and Apte et al. (2015), respectively. From this range we have developed a global default primary $PM_{2.5}$ CF based on the average and range of the city distributions. These factors are "recommended," but will not be strongly recommended until robustness tests are performed and future papers published about the approach.

For outdoor emissions and exposures to direct $PM_{2.5}$ from stacks in urban areas, interim recommended generic factors are calculated for very high, high, and low stack based on ground level using the correction factors from Humbert et al. (2011). CFs will become recommended after an effort is made to update latest available iF from point sources for high stack emissions. For direct PM emissions in the rural archetype, we have established recommended CFs based on the multi-compartmental, indoor-outdoor model developed for this project. There, CFs will be provided as global default values with distributions reflecting worldwide variations and regional defaults (for the USEtox regions, http://usetox.org) with distributions reflecting within-region variability.

For urban and rural exposures to secondary $PM_{2.5}$ we have developed Interim recommended factors for urban and rural archetypes based on intake fractions for secondary $PM_{2.5}$ precursors based on Humbert et al. (2011), and apply the same ERFs as for ground level primary $PM_{2.5}$.

To allow compatibility with ERFs for emissions indoors that include marginal changes at low and high exposure background concentration levels, we provide CFs for indoor emissions of and exposure to direct $PM_{2.5}$ at a low exposure level in the range 10-20 μg/m^3, and a high exposure level in the range of 250 μg/m^3. For the low exposure level typical of homes in the developed world, we consider low and high ventilation rates and apply the same ERF as for outdoor $PM_{2.5}$. For the high exposure range typical of homes with solid fuel cooking indoors, we have an interim recommended CF for the low ventilation scenario (considered unlikely) and a recommended CF for the likely high ventilation scenario – both making use of the indoor ERF from the global burden of disease (GBD) study for cook stove exposures.

We address secondary $PM_{2.5}$ formation indoors for both high solid fuel combustion driven concentrations and for situations where secondary $PM_{2.5}$ arises from interactions of volatile precursors indoors with ambient ozone. For high background concentrations indoors associated with solid fuel combustion, the secondary $PM_{2.5}$ formation is already accounted for in available emissions factors and thus does not need a separate modeling approach. For secondary $PM_{2.5}$,

Table 4.4: Matrix of recommendations for characterization factors for indoor emissions of $PM_{2.5}$ and secondary $PM_{2.5}$ precursors.

		Closed building	
		Low ventilation rate	High ventilation rate
Primary $PM_{2.5}$ based on Hodas et al. (2016)	Low background concentration level 10-20 Mg/m^3	Recommended: **Urban generic archetype** for closed building • **Same exposure-response** per kg in as for outdoor	Recommended: **Generic archetype**
	High background concentration level 250 Mg/m^3	Interim recommended value *(unlikely scenario)*	Recommended: **solid fuels archetype** with high ventilation • ERF based on indoor concentration and GBD curve
Secondary $PM_{2.5}$		Roadmap for secondary characterization factors	• For solid fuels, secondary $PM_{2.5}$ formation is already included in $PM_{2.5}$ emission factors (total is measured)

formation indoors associated with volatile emissions indoors interaction with outdoor concentrations of reactive species, such as ozone, we have laid out a roadmap for a modeling approach for secondary $PM_{2.5}$ formation that is compatible with our multi-compartment modeling approach.

4.7.3 Applicability, maturity, and good practice for factors application

The procedures outlined in this chapter provide CF factors that capture the global central ranges for CFs but also allow for exploration of variability among cities and regions. There are variations in impact per kg $PM_{2.5}$ emitted (or per kg secondary $PM_{2.5}$ precursor emissions) that can be addressed through a stepwise application of spatially differentiated ranges for the most sensitive parameters in an emissions-to-health effects calculation.

For $PM_{2.5}$ and secondary $PM_{2.5}$ precursor outdoo emissions, the most important parameters for setting the range of health impact per kg release are linear population density; the dilution factor, which is the inverse of the wind-speed mixing height product; background $PM_{2.5}$ concentration; and background mortality.

For $PM_{2.5}$ and secondary $PM_{2.5}$ precursor indoor emissions, the most important parameters for setting the range of health impact per kg release are indoor air changes per hour; occupants per m^2; use of filtration; background $PM_{2.5}$ concentration indoors; and background mortality.

The approach presented here allows users to address variability in CF based on regional variations and the location of emissions – we have not yet provided a process for fully addressing uncertainty.

4.7.4 Link to inventory databases and their needs

The appropriate application of the CFs for $PM_{2.5}$ will require databases that provide emissions factors specifying $PM_{2.5}$ and $PM_{2.5}$ outdoor precursor emissions factors at regional scales. Default global values will also need to be provided, but with higher uncertainty ranges.

4.7.5 Roadmap for additional tests

The CFs for exposure to primary $PM_{2.5}$ from ground level emissions will not be strongly recommended until there is an opportunity to test the robustness of the approach, in particular the linkage between the results obtained using a global default versus city-specific values.

A roadmap has been established for updating secondary $PM_{2.5}$ characterization factors, based on spatially explicit models. This includes the following steps:

a) Perform a systematic sensitivity study over the entire US to analyze the spatial variation of the formation rate of secondary $PM_{2.5}$ and intake fractions using the Intervention Model for Air Pollution, InMAP (Tessum et al. 2015), and compare it to outputs of the Community Multiscale Air Quality (CMAQ) model with decoupled direct methods (DDM), isolating the contribution of individual precursors (Buonocore et al. 2014).
b) Identify archetypes for secondary $PM_{2.5}$ as a function of population density and main limiting substance in the considered region (NH_3, SO_2, and organic carbon).
c) Extend the analysis to world level. Provide characterization factors for emissions of secondary $PM_{2.5}$ precursors based on both marginal and average responses, using a tiered approach corresponding to different levels of spatialization.

The process for assessing secondary $PM_{2.5}$ formation both outdoors and indoors requires continuing monitoring of the $PM_{2.5}$ health effects literature to assure an adequate set of case studies globally for evaluating the reliability and representativeness of secondary $PM_{2.5}$ CFs.

There remains a need in this effort to assess uncertainty by reviewing the emissions to impact factors that have significant data gaps and/or lack mechanistic understanding. This effort will be supported by a sensitivity analysis that flags parameters that have a strong influence on model the CF analysis outcome.

4.7.6 Next foreseen steps

The next major step in this effort is building the models and databases that can transparently and reliably provide the CFs outlined as recommended and interim recommended factors in Table 4.3 and Table 4.4. We have built and tested a multi-compartment model that tracks primary $PM_{2.5}$ emissions within a series of embedded indoor and outdoor urban and rural environments. A manuscript describing this model is in preparation and will be published within near term. The model needs continued testing and evaluation, but will be made available. Efforts to include secondary $PM_{2.5}$ in this model format have just begun with results expected within one year.

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5. Water use related impacts: Water scarcity and human health effects

Part 1: Water Scarcity
Anne-Marie Boulay, Stephan Pfister, Masaharu Motoshita, Urs Schenker, Lorenzo Benini, Shabbir H. Gheewala, Maria Clea Brito de Figueiredo, Kevin Harding

Part 2: Human Health Effects
Masaharu Motoshita, Anne-Marie Boulay, Stephan Pfister, Lorenzo Benini, Maria Clea Brito de Figueiredo, Shabbir H. Gheewala, Kevin Harding, Urs Schenker

Water consumption can lead to deprivation and negative impacts on human health and ecosystems quality. The detailed impact pathway framework has been previously presented by Bayart et al. (2010), Kounina et al. (2013) and Boulay et al. (2015). In this chapter, a simplified version of the framework is considered (Figure 5.1), and the harmonization efforts focused on i) a generic water scarcity impact category ("stress-based generic midpoint"), which is not directly connected to damage categories, but represents the potential to deprive either human users or ecosystems users, and ii) the human health impact pathway ("Impact on human health," in Part 2 of this chapter (p.118)). The recommended methods are meant to assess potential impacts associated with marginal water consumption as assessed in LCA. Recommendations for non-marginal applications are foreseen as future work (section 5.9.4).

The outcome of this work is closely linked to the work performed by the UNEP-SETAC Water Use in LCA (WULCA) working group. This work started with the proposal of the framework for including water use impacts in LCA and was followed by a qualitative review of existing water assessment methods (Kounina et al. 2013) and a quantitative comparison of the existing methods for water scarcity and human health impacts (Boulay et al. 2015b). Many of the recommendations in this chapter are therefore based on previous work performed by WULCA. Work on ecosystems and resources damage categories is ongoing within the WULCA working group, but not yet mature for consensus.

PART A: WATER SCARCITY

5.1 Scope

According to the ISO 14046 standard (ISO 14046. 2014), water scarcity is the "extent to which demand for water compares to the replenishment of water in an area, such as a drainage basin." In the past, most water scarcity indicators were defined to be applicable either for human health or ecosystems impacts even though they are sometimes related (Boulay et al. 2014). However, in addition to these scarcity indicators, WULCA decided that absolute scarcity (availability per area) is a relevant aspect to be reflected in the impact category indicator.

The intention of the water scarcity indicator documented in this chapter is to serve as a generic impact category indicator for water scarcity, without necessarily being located at any specific point on the cause-effect chain of either the human health or the

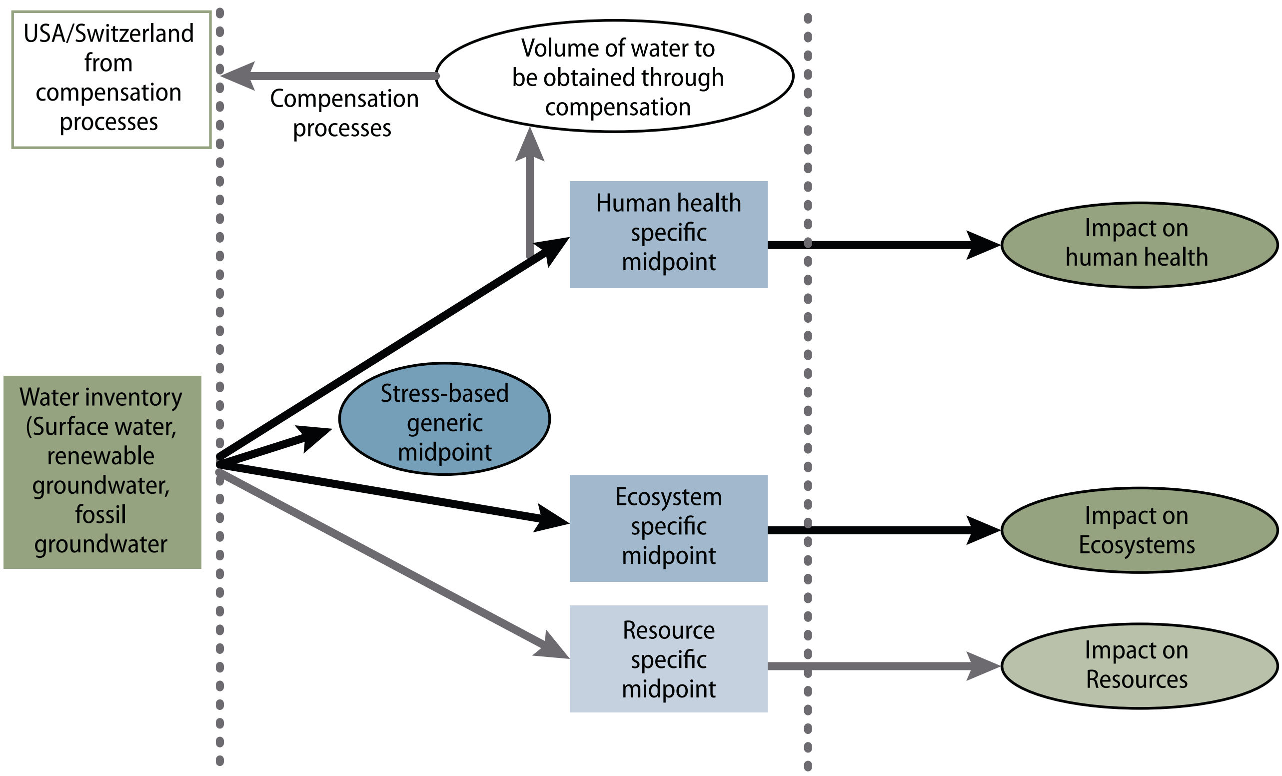

Figure 5.1: Simplified framework for water consumption impacts assessment in LCA. Adopted from Boulay et al. (2015c).

ecosystem quality endpoint indicator. This is to satisfy the need of LCA practitioners for one simple indicator that can be used for simplifying LCA studies, when the interest or complete impact models for a full damage assessment on human health or ecosystem quality are not available.

The goal is to assess marginal changes in a system, i.e., that the water consumption of the analyzed system is not significantly changing the water scarcity on its own.

5.2 Impact pathway and review of approaches and indicators

The WULCA working group first evaluated indicators based on the Withdrawal-to-Availability (WTA) concept. It was found that this approach does not take into account that significant amounts of water may be withdrawn but released into the same watershed (e.g., turbined or cooling water), sometimes within a very short time period. Therefore, it was suggested to rely on Consumption-to-Availability (CTA)-based approaches that only consider the portion of water which is no longer available in the same watershed, because it has been evaporated, integrated into a product, or released into a different watershed or the sea.

Watershed in this context relates to those provided in WaterGAP, which are not differentiating sub-watersheds, such as done by Loubet et al. (2013) and Scherer et al. (2015). While their work showed relevance of such assessment, the global models are too uncertain on this level of detail for our purpose.

Given that the generic impact indicator is required to represent water scarcity that affects human health and ecosystem quality, the CTA concept was then further developed to also contain ecosystems water requirements (EWR). Demand-to-Availability (DTA) was therefore introduced as a new concept where demand covers human and ecosystems water requirements.

Several indicators have been proposed in the process, as described in more detail in Boulay et al. (2015c). The following two were carried into a deeper analysis:

- The first one, called $DTA_{X,}$ multiplies the conventional DTA indicator by a factor (Area/Availability)$^{0.34}$, to better represent the lack of water availability in arid areas. DTA is the direct ratio of the total demand from human and ecosystems divided by availability (in analogy to WTA or CTA).
- The second one is based on the Availability-minus-Demand (AMD) as an indicator, using the inverse of this (1/AMD) as a basis for the scarcity factor (see further description in section 5.4 below). When demand becomes similar (or larger than) availability, this indicator is set to a maximum in order to avoid infinite or negative results.

The experts in the WULCA working group established four criteria to analyze the DTA_X and 1/AMD indicator, as described in further detail in (Boulay et al. 2016) and Table 5.1.

Table 5.1: Decision criteria to recommend a generic impact category indicator (adapted from Boulay et al. 2016)

Criteria	DTAx	1/AMD
Stakeholders acceptance	Low (3/33) Only academics (one is a part-time consultant)	Good (26/33) Academics, consultants, and researchers in industry and government
Robustness with closed basins	*Limpopo* Shows higher scarcity than in 1/AMD (ranking and absolute value percentile)	*Ganges, Yellow River, Darling, Colorado, Nile, Jordan, Indus, Syr Darya and Amu Darya* Show higher scarcity than DTAx (ranking and absolute value percentile)
Main Normative choice	Absolute and relative availability have equal contribution to impacts *(x = 0.34)*	Regions where demand is equal or higher than availability are set as maximal *(equation is discontinuous)*
Physical meaning	Two physical quantities, empirically combined in an index with no physical units	Express a physical meaning up to the point where demand is equal or higher than availability

Given the preferred performance of 1/AMD in all criteria (Boulay et al. 2016) this has become the basis for the recommended scarcity indicator method, called Available WAter REmaining (AWARE).

5.3 Description of indicator(s) selected

The AWARE method assesses the relative potential of water deprivation, to either humans or ecosystems. The indicator in the AWARE method builds on the assumption that the less water remaining available per area, the more likely another user will be deprived (Boulay et al. 2016). Water remaining available per area refers to water remaining after human water consumption and environmental water demand has been subtracted from the natural water availability in the drainage basin.

5.4 Model, method and specific issues addressed

> "The 1/AMD indicator is based on the inverse of the difference between availability and demand instead of the ratio (Eq. 1 and 2). It can be interpreted as a surface-time equivalent to generate unused water in this region up to the point where D = A. When the value of the demand is equal to or larger than the availability (negative AMD), the factor has to be set at a maximal value since the equation would no longer be continuous nor hold the same meaning (Eq.4a). This maximal value of 100 is set as a cut-off after the CF has been normalized (Eq.3), and a minimum value of 0.1 is applied as a lower cut-off (Eq.4a and 4b)."

This is taken from and further described in Boulay et al. (2016). The CF are originally calculated on a monthly time step.

> "Where Demand refers to the sum of human water consumption (HWC) and environmental water requirements (EWR) and both Demand and Availability are calculated in m^3/month and Area in m^2. AMD_i is calculated in $m^3\ m^{-2}\ month^{-1}$ and the remaining volume of water available for use once demand has been met, per unit area and time ($m^3\ m^{-2}\ month^{-1}$). Since this factor is expressed relative to the area, comparability across region is ensured. Its inverse, STe_i, is expressed in $m^2\ month\ m^{-3}$, can be interpreted as the Surface-Time equivalent required to generate one cubic meter of unused water in this region (assuming a given level of water demand)." (Boulay et al. 2016).

In other words, this refers to a hypothetical equivalent of land surface necessary to obtain a certain amount of water over a certain period of time, considering local water availability minus the local demand. The value of $AMD_{world\ avg}$ is the consumption-weighted average of AMD_i (m^3/m^2 month) over the whole world (0.0136 m^3/m^2-month), obtained over the 11 050 sub-basins and twelve months. Units of the CF are dimensionless and expressed in m^3 world eq./m^3_i (Eq. 3).

The CF value of 1 corresponds to the region where the world average availability minus demand (AMD) occurs ($AMD_i = AMD_{worldavg}$). This is an internal normalization used in the modeling in order to provide results relative to a reference as a basis for interpretation. While a different reference (such as the Amazon or the Sahara) would have changed the absolute values, the relative results between watersheds would remain the same. It should be noted that a CF value of 1 is

$$AMD_i = \frac{(Availability - HWC - EWR)}{Area} \qquad \text{Eq.1}$$

$$STe_i = \frac{1}{AMD_i} \qquad \text{Eq.2}$$

$$CF = \frac{STe_i}{STe_{world\ avg}} = \frac{AMD_i}{AMD_i} = \frac{AMD_{world\ avg}}{AMD_i}, \text{ for Demand<Availability} \qquad \text{Eq.3}$$

$$CF = Max = 100, \text{ for Demand} \geq \text{Availability in region i or } AMD_i < AMD_{world\ avg}/100 \qquad \text{Eq.4a}$$

$$CF = Min = 0.1 \text{ for } AMD_i > 10 \times AMD_{world\ avg} \qquad \text{Eq.4b}$$

not equivalent to the factor for the average water consumption in the world, i.e., the world average CF to use when the location is not known. This value is calculated as the consumption-weighted average of the CFs, which are based on 1/AMD and not AMD, hence the world water consumption-based average has a value of 43 m^3 world water-eq/m^3 for unknown use and 20 m^3 world water-eq/m^3 and 46 m^3 world water-eq/m^3 for non-agricultural and agricultural water consumption, respectively (see next section for guidance on when to use them). Characterization factors were computed using monthly estimates of sectoral consumptive water uses and river discharge of the global hydrological model WaterGAP (Müller Schmied et al. 2014). Environmental Water Requirements (EWR) were included based on Pastor et al. (2014) which quantifies the minimum flow required to maintain ecosystems in "fair" state (with respect to pristine), ranging between 30-60% of natural flow.

5.5 Characterization factors

Characterization factors of the AWARE method are shown in Figure 5.2 below, and are available for download from http://www.lifecycleinitiative.org/applying-lca/lcia-cf.

A number of characterization factors (CF) for the AWARE model have been developed, featuring different spatial and temporal resolutions, in order to meet the range of demands from potential users in terms of both specificity and applicability (e.g., background processes). Aggregation is based on consumption-weighted averages of the underlying monthly and basin-related CFs. Thus, when the exact basin or month in which the water consumption occurred is unknown, the aggregated CF acknowledges that it is more likely to have happened in the basin or month with the highest relative consumption. This is done separately, for the specific user type pattern of irrigation and non-irrigation water use, as well as total water use. The calculations are specified below (details in Section 5.12):

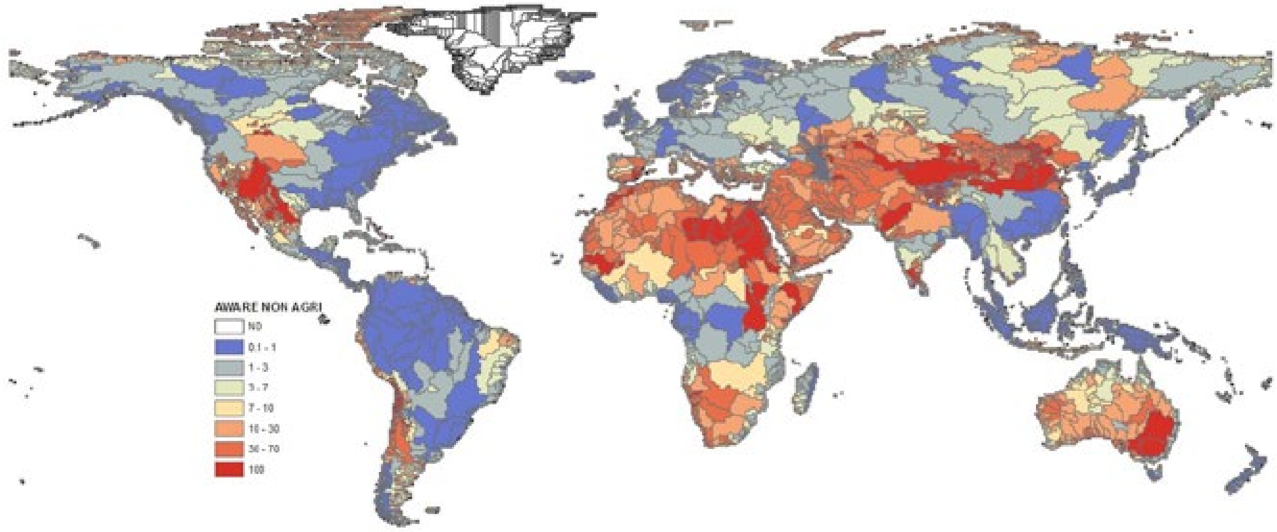

Figure 5.2: AWARE Annual CF shown for non-agricultural use (arithmetic average of CF over twelve months)

Table 5.2: CF (m^3 world eq./m^3_i) for the main regions of the world, for both types of use, or unknown use

Regions	Agri	Non-Agri	Unknown
Europe (RER)	40.0	21.0	36.5
Rest of the world (RoW)	46.0	22.3	44.0
Africa (RAF)	77.4	51.3	73.9
Asia (RAS)	44.6	26.0	43.5
Latin America and the Caribbean (RLA)	31.4	7.5	26.5
North America (RNA)	35.7	8.7	32.8
Middle East (RME)	60.5	40.9	60.0
OECD	41.4	20.5	38.2
OECD+BRIC	36.5	19.5	34.3
Oceania	69.6	19.8	67.7

- CF resolved at monthly and watershed scale: CF_$_{ws,m}$;
- CF resolved at the spatial scale (watersheds) but aggregated over time (yearly-scale) and separated by sectoral (agricultural or non-agricultural) water consumption: CF_agri$_{ws,y}$; CF_non-agri$_{ws,y}$;
- CF resolved at the temporal scale (months) but aggregated over space (country-scale) and separated by the sectoral consumption: CF_agri$_{c,m}$; CF_non-agri$_{c,m}$;
- Country-specific CF averaged over space and time and separated by sectoral water consumption (agr or non-agr): CF_agri$_{c,y}$; CF_non-agri$_{c,y}$;
- Country-specific default CF averaged over space and time: CF_default$_{c,y}$;
- Continental/region-specific CF averaged over space and time: CF_default$_{r,y}$;
- Global CF averaged over space (watersheds) and time (months) : CF_default$_{g,y}$

5.5.1 Seasonal variability

The maps below show the maximum difference observed across CFs within the same watershed by comparing the minimum to the maximum monthly value. The analysis distinguishes between agri (Figure 5.3) and non-agri factors (Boulay et al. 2016). Domestic and industrial water use do not vary as importantly between months as agricultural water use. Within WaterGAP v2.2 (Müller Schmied et al. 2014), non-agricultural water consumption is even modeled to be constant over the year. That is why the highest variability is observed for those catchments in which agricultural water consumption and/or EWR vary most among months. The Figure clearly shows in which regions of the world temporal resolution is highly important for proper assessment of water scarcity. Information regarding the relative standard deviation (coefficient of variation) associated with the aggregation over time is provided in form of tables and maps in Boulay et al. (2016) for each of the levels of aggregation described above.

5.5.2 Variability over space

The highest spatial resolution of the analysis is at the scale of the watershed defined within the WaterGAP model v2.2 (Müller Schmied et al. 2014). Spatial variability is depicted in the maps below as the difference between annual (agricultural) characterization factors calculated at the catchment scale and the country average (agricultural) (Figure 5.4). A similar analysis for non-agricultural CF is available in Boulay et al. 2016. The highest differences can be observed in those countries that have the highest diversity in water consumption and/or EWR across the watersheds included within the country boundaries. The Figure clearly shows in which regions of the world spatial aggregation leads to deviating results in water scarcity assessment. Information regarding the relative standard deviation (coefficient of variation) associated with the aggregation over space is provided in form of tables and maps in Boulay et al. (2016) for each of the levels of aggregation described above.

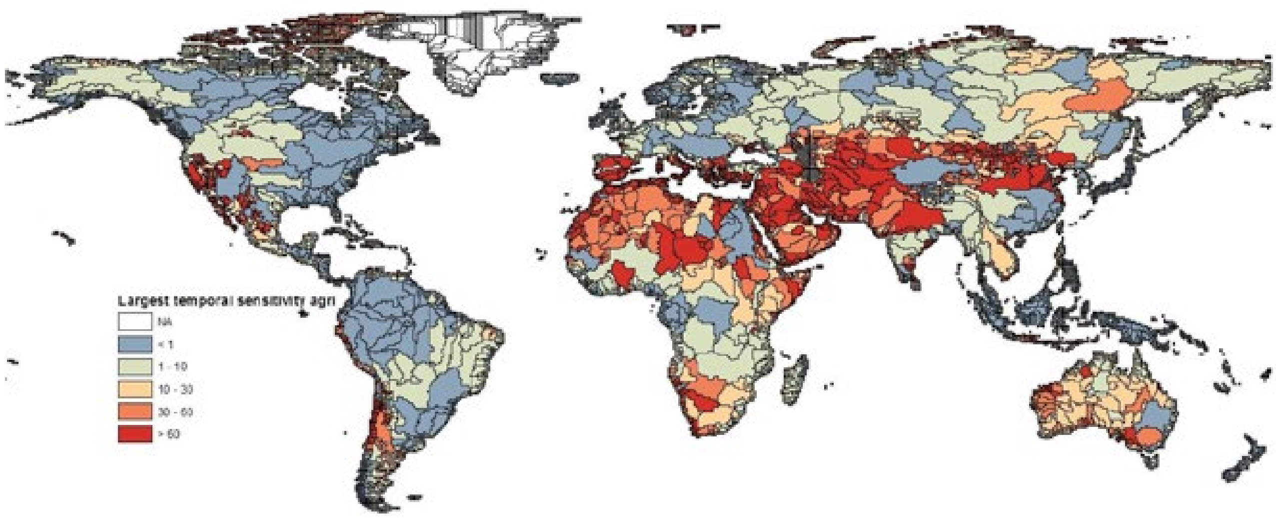

Figure 5.3: Largest temporal variability in annual AWARE CF, shown for agriculture use (similar for non-agricultural use), from Boulay et al. 2016.

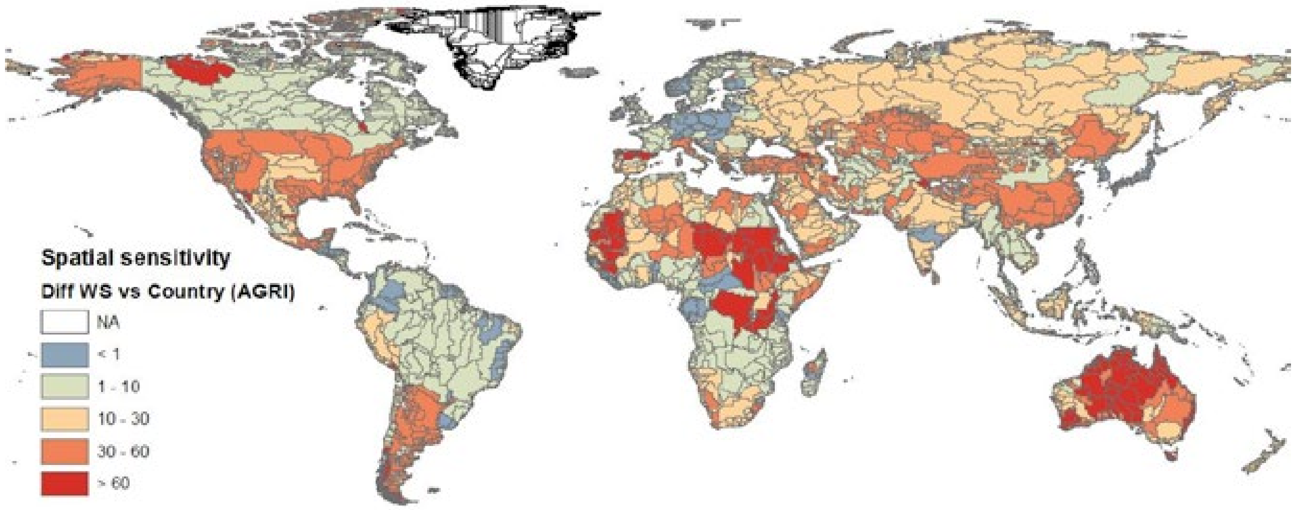

Figure 5.4: Sub-national variability of agricultural CF, computed as the difference between annual characterization factors calculated at the catchment scale and the country average.
(Similar for non-agricultural use), from Boulay et al. 2016.

5.5.3 Variability-induced uncertainty associated with characterization factors aggregated in time and space

Any aggregation entails losing information. The loss of information associated with a weighted average depends on the level of aggregation (i.e., time and/or space) and might result in an over- or underestimation of the value of the characterization factor. Information regarding the relative standard deviation (coefficient of variation) is provided online in form of tables and maps for each of the levels of aggregation introduced above.

5.5.4 Uncertainty associated with the underlying hydrological model

The uncertainty of the underlying global hydrological model WaterGAP v.2.2 has not been quantified. Monthly output is more uncertain than annual output. The water availability component was calibrated by the model developers against mean annual river discharge at 1 319 gauging stations; moreover, the adjusted calibration factor is regionalized to grid cells outside the calibration basins. However, uncertainty of monthly water availability is high, in particular in dry regions, as revealed e.g., by Scherer et al. (2015). Estimates of agricultural water consumption, which accounts for approximately 90% of global water consumption, strongly depends on estimates of irrigated area, cropping period, and climate variables (Döll et al. 2016) The soundness of the underlying assumptions made for the computation of non-agricultural water use is discussed by Flörke et al. (2013)

5.5.5 Uncertainty and sensitivity associated to Environmental Water Requirement (EWR)

EWR has been identified as one of the factors expected to contribute most to the uncertainty of the characterization factors. This is due to methodological uncertainties associated to the definition of EWR. A state-of-the-art, monthly assessment for EWR was used in the AWARE method (Pastor et al. 2014), but challenges remain. As reported by Boulay et al. (2016):

> *"EWR used vary monthly as a function of flow patterns but not as a function of other environmental aspects and the algorithm calculating EWR at global scale does not account for specific local aspects due to limited data access at global scale (river width, global aquatic fauna, etc). Moreover, although the underpinning data includes information about the location of dams, there is variation and uncertainty about the ways in which these infrastructures are managed. In some cases, the management of dams includes specific water releases to meet environmental flow requirements."*

The sensitivity of the AWARE indicator to EWR was tested for a variation of +/- 20% in the absolute value of EWR. Each of the minimal and maximal resulting values of the factors show a 98% consistency with the original values, using the rank correlation coefficient as reported in Boulay et al. (2015a). This value goes to 96% (meaning that the rank of the watersheds is maintained at 96% of the cases) when comparing the minimum and maximum values of the factors, hence the total variation of EWR of 40% (plus and minus 20%). Only 3% of the world area passes beyond the point of "demand > availability" on an annual level, corresponding to 11% of the world water consumption when an upper value of EWR+20% is used (Table 5.3). However, the use of a different method for EWR (Richter et al. 2012) would result in higher change in the value of the characterization factors for a significant number of world's watersheds (e.g., 21% and 50% of the world water consumption would reach the maximum CF level by this choice for all 12 months or at least one month, respectively).

5.6 Normative choices

The following modeling choices are normative: definition of the cut-off levels (0.1, 100) and normalization of 1/AMD by weighted world average. The underlying equation of the AWARE characterization factors is defined on the basis of normative choices, like the LCIA models of all available water scarcity characterization factors. However, up to the point in which cut-offs apply, the model keeps a close link to physical meaning. The selection of the cut-off values has the objective to limit the potential influence of extreme low or high values while minimizing the loss of information i.e., the number of watersheds having a CF above the maximum cut-off value 100 or below the minimum cut-off value 0.1 (Figure 5.5).

5.7 Limits of the method

The three main limitations of this method are:

1. The lack of discriminatory power in regions where demand is larger than availability (identified as main normative choice in the Table above). This implies that the maximal deprivation potential is reached in these regions (CF = 100), for a certain amount of months, as shown in Figure 5.6 (next

Table 5.3: Percentage of the world water consumption affected by cut-off choices and sensitivity to EWR modeling choices, monthly, and annual (adapted from Boulay et al. 2016).

	AWARE		AWARE if using EWR -20%		AWARE if using EWR +20%		AWARE if using EWR Richter (80%)	
	For all 12 months	For at least one month	For all 12 months	For at least one month	For all 12 months	For at least one month	For all 12 months	For at least one month
Cutoff choice AMD_{world}> $100 \times AMD_{region\ I}$ (100)	< 1%	5%	< 1%	7%	< 1%	2%	< 1%	< 1%
Modeling choice for Demand> Availability set to maximal value (100)	4%	33%	2%	20%	11%	50%	21%	50%
Cutoff choice for AMD_{world} < $0.1 \times AMD_{region\ i}$ set to minimum (0.1)	< 1%	< 1%	< 1%	< 1%	< 1%	< 1%	< 1%	14%

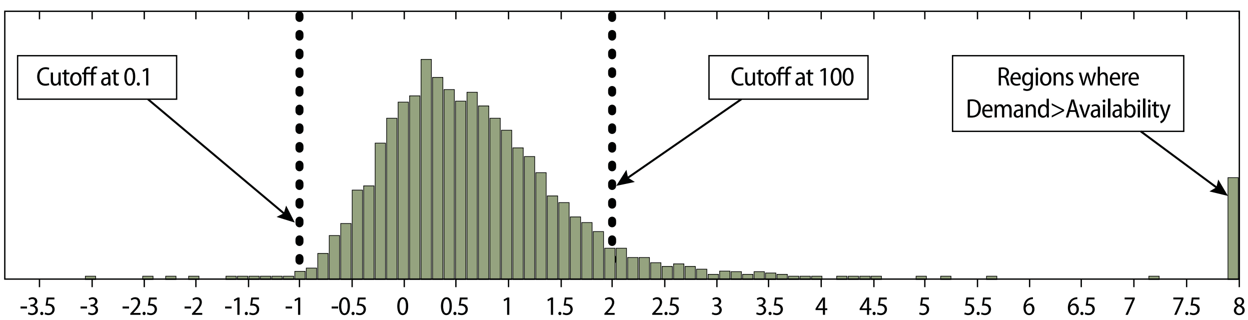

Figure 5.5: Log-scale probability distribution function of the AWARE CFs calculated at the watershed scale (Boulay et al. 2016)

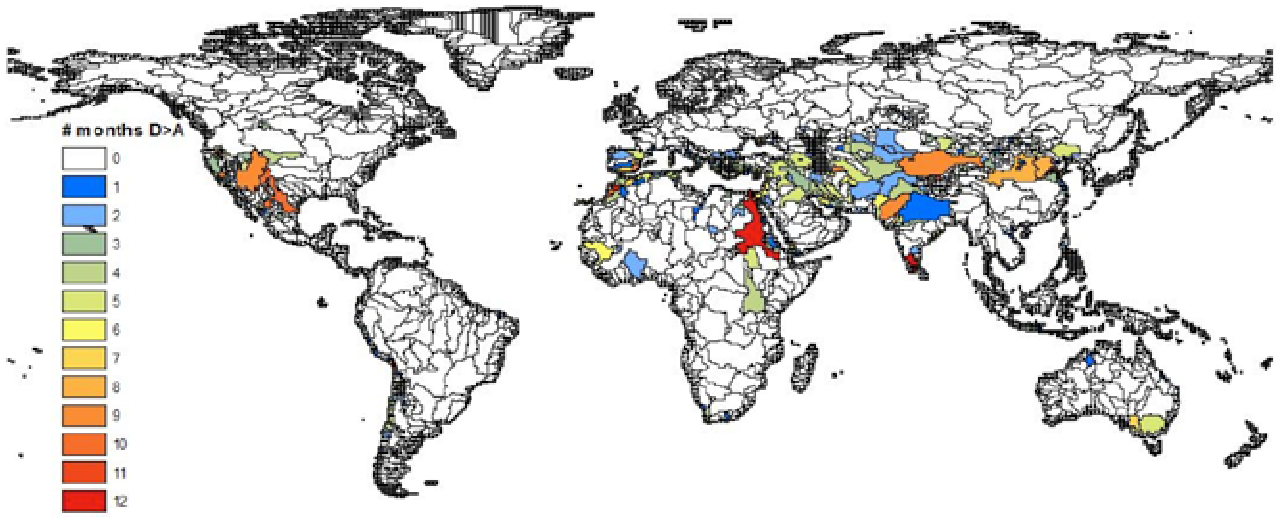

Figure 5.6: Number of months where demand is larger than availability and CF is set to 100

page) and discussed in Boulay et al. (2016). On an annual basis only 8% of the world consumption is located in these regions (when using annual values averaged on twelve months without weighting) and this was judged as an acceptable loss of information, even if on monthly level it affects a higher share as further detailed in Boulay et al. (2016).

2. The uncertainty and normative nature of the choice of EWR. The quantification of EWR involves expert choices and hypotheses regarding the "fair" status of aquatic ecosystems with respect to a pristine environment. The method chosen, which is considered state-of-the art, is the latest and the only one providing monthly values for the fraction of the flow, ranges between 30-60% necessary to maintain the desired state, and it is the only global method that evaluates EWR on a monthly basis validated with several case studies across five different freshwater eco-regions (Pastor et al. 2014). However, different methods would have provided different values, one of them being set constantly at 80% of the annual flow (Richter 2013). Using such a different method would change the curve and values of the resulting indicator, and this is further described in Boulay et al. (2016).

3. "The span of this new CF is chosen to be three orders of magnitude, between 0.1 and 100. In previous midpoint methods, this varied from two orders of magnitude (0.01 – 1) for Pfister et al. (2009) and Berger et al. (2014), and up to 5, 7 and 9 orders of magnitude for Boulay et al. (2011), Hoekstra et al. (2012), and Swiss Eco-Scarcity method (Frischknecht et al. 2008), respectively, excluding the zero values. This was an important choice that was made with the thresholds placed along the distribution curve in order to keep as much of the natural distribution as possible yet fix the tailing values to the maximum and minimum. This normative choice of a maximal range of 3 orders of magnitude was based on expert judgment. Previously, the group and expert consultation suggested 4 orders of magnitude as acceptable, but the analysis of the preliminary results revealed that 3 orders of magnitude was comparable to typical variation within inventories (such as electricity production, water consumed per capita and the case study on rice; Frischknecht et al. 2016) and therefore meaningful for a balanced between LCI and LCIA. Moreover, it provided a better balance for decision makers between the choice of geographical location and the improvement in water efficiency, which was not the case with an indicator spreading over 4 orders of magnitude, as initially considered. Reducing it to two orders of magnitude (cut-off of 10) was also considered but the cut-off was judged too influential and resulting in a too large loss of discriminatory power for regions with less than one tenth remaining water than the world average." (Boulay et al. 2016).

5.8 Rice case study application

The rice case study is presented in Chapter 3.7. Water consumption in all three scenarios is highly dominated by the rice cultivation phase (more than 99.4%), and therefore the other production stages have been

Table 5.4: Results of the rice LCA case study (functional unit: 1 kg of cooked white rice)

Case	Water Consumption (m^3/FU) in rice production (share of total water consumption in %)	Watershed	CF AWARE (m^3 eq/m^3)	CF DTAx	Impact AWARE (m^3 eq/FU)	Impact DTAx (m^3 eq/FU)
Rural India	0.78 (99.9%)	Average	30	3.1	23	2.4
		Ganges	13.82	0.71	10.74	0.55
		Godavari	2.22	0.63	1.72	0.49
Urban China	0.46 (99.5%)	Average	45	3.4	21	1.6
		Yellow River	90.58	1.49	41.50	0.68
		Pearl river	0.49	0.34	0.22	0.16
USA-Switzerland	0.08 (99.4%)	Average	36	3.9	2.9	0.31
		Redriver	0.15	0.21	0.01	0.02
		Arkansas River	2.66	0.74	0.21	0.06

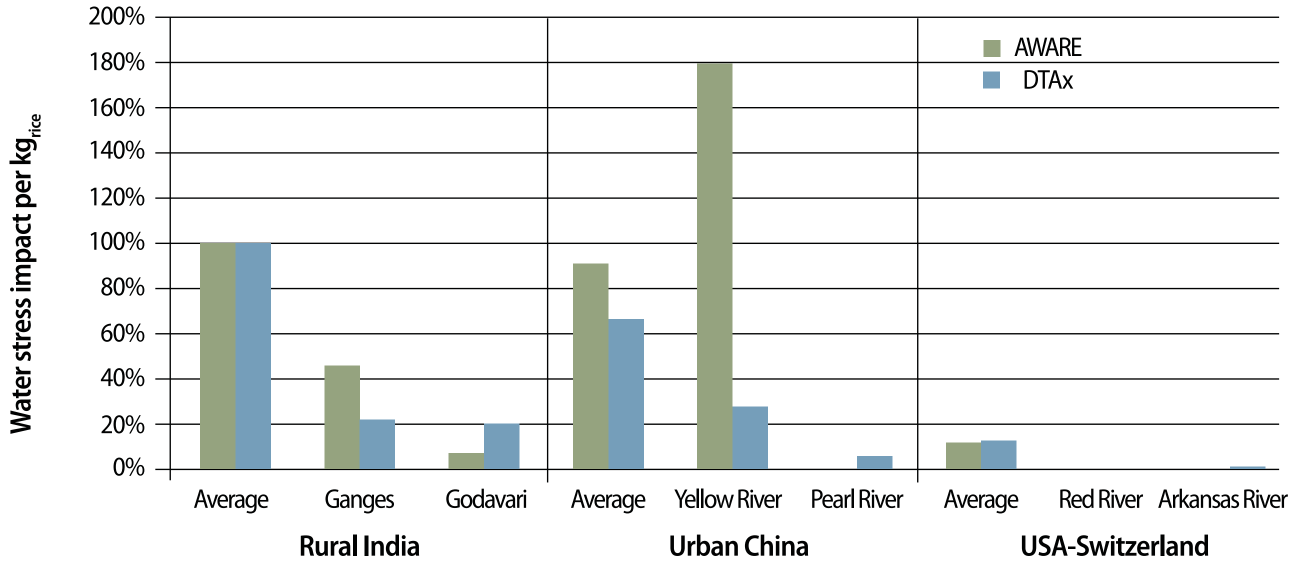

Figure 5.7: Water stress impacts per kg of cooked white rice for AWARE and DTAx

Impacts are presented relative to the low production scenario for average India in the rural India case, based on Table 5.5.

neglected in this analysis. The rice production in the USA-Switzerland scenario is having the lowest water consumption, followed by the one in urban China (Table 5.4).

The national average characterization factors for agricultural production are similar in all three countries (China, India, USA) for both, AWARE and DTAx, compared to the overall span of the CFs. As a result, the LCIA results are very similar to the life cycle inventory results.

As mentioned in section 5.7, national averages are not satisfactory for foreground processes and watershed-specific and time-specific CFs should be applied. Information regarding the rice production time schedule was not available. We only further differentiated the rice production locations in each country. For this purpose, we selected two major watersheds where rice is produced within each country: Ganges and Godavari in India; Yellow River and Pearl River in China; and Red River and Arkansas River in the US.

In the case of rural India and the USA-Switzerland, both major watersheds have lower characterization factors than the national average for both DTAx and AWARE. The Pearl River in India is consistently assessed to have lower impacts than the national average - a factor of 93 for AWARE and 10 for DTAx. In the case of USA, where rice production is restricted to a small area around the state of Arkansas (see Figure 5.8), AWARE CF is 13 to 243

Figure 5.8: Irrigated rice production (adjusted from Pfister et al. 2011)

Light grey indicates low, and dark grey high irrigation water consumption per kg of rice produced. Red circles indicate location selected for watershed assessments.

times lower than the USA average, while for DTAx, it is between 5 and 19 times lower (the difference being associated with the different span of the methods). In the case of urban China, the Yellow River has an AWARE factor of twice the national average while in DTAx, the value is half of the national average.

The ranking of different production systems is depending on the production location within a country rather than between producer countries. It needs to be kept in mind that life cycle inventory results also vary as a function of location (more or less irrigation water required dependent on the location), which is not considered here due to lack of information.

While the detailed assessment shows some changes in the ranking as a function of the cultivation site, it also shows that the two indicators have a different behavior: in the case of rural India, Ganges and Godavari watersheds have a similar DTAx but a factor five difference in AWARE CF, due to the different range of both methods. However, a larger difference and inverted pattern is seen for the Yellow River in China, where DTAx predicts lower, and AWARE higher, CF than the national average. This is likely explained by the fact that in DTAx, more weight is given to the availability, a power of 1.34, whereas in AWARE this is less than 1 (demand is subtracted form availability). The Yellow River is one of the analyzed watershed considered a closing basin (Kijne 2003) with more than 200 no-flow days at the mouth of the river already in 1997 (Falkenmark and Molden 2008) and described as an area of intense competition (Molden 2007). This confirms the choice of AWARE as better representing areas of high availability but also high competition such as the Yellow River.

These three scenarios are only for a plausible illustration, and not representative at all of the situations expected in different countries.

5.9 Recommendations and outlook

5.9.1 Main recommendation

AWARE is the recommended indicator based on Boulay et al. (2016) as described above. These characterization factors are available for download from http://www.lifecycleinitiative.org/applying-lca/lcia-cf. We strongly recommend that a sensitivity analysis be performed with a conceptually different method, such as WSI (Pfister and Bayer 2014), WAVE (Berger et al. 2014), alpha scarcity (Boulay et al. 2011) or DTA_x (as presented here and available online www.wulca-waterlca.org) and the results discussed.

5.9.2 Judgment on quality, interim versus recommended status of the factors and recommendation

This recommendation is final. It was considered an interim until 10 case studies were performed with sensitivity analysis using other conceptually different methods, including DTA and DTAx, and analyzed without unjustifiable discrepancies by the AWARE authors by July 2016. This also included uncertainties on EWR (EWR ranges) and showed consequences of the choice of different maximum cut-off (10 and 1000) in assessing AWARE results for case studies, with each aspect demonstrated in at least 2 case studies. The studies revealed general agreement of trends but also highlighted differences, which are assessed to be reasonable. The studies can be found online on the WULCA webpage.

5.9.3 Applicability or maturity and good practice for factors application

AWARE is applicable for any study considering specific location and time; nevertheless maturity is still limited as the method has only been applied in a small number of case studies. Some of the case studies have presented discrepancies between country-scale characterization factors and processes' contribution to total impacts, when conceptually different methods are applied. Some of the country-scale characterization factors of AWARE may look counterintuitive if they are erroneously interpreted as measures of overall country scarcity. Instead, they represent the marginal impact generated by small interventions (i.e., this group suggests lower than 5% of overall water consumption in a given area). Additionally, the influence of the cut-off (recommended at 100, but tested for 10 and 1000) is particularly significant for regions with higher AWARE value (i.e., lower remaining water). The characterization factors provided together with this publication are recommended for marginal water use applications only (e.g., changing the watershed water consumption by less than 5%).

5.9.4 Next foreseen steps

Foreseen work includes the calculation of non-marginal characterization factors to be used, for example, for the calculation of national water footprints.

It is also suggested for future work that the calculation of CF aggregated on country and annual levels is done to represent crop-specific patterns based on growing seasons and watersheds, in order to further differentiate the AGRI CF into crop-specific CF, when month and watershed are unknown.

5.10 Acknowledgements

This task force acknowledges the contribution and work from the WULCA members who co-authored the paper Boulay et al. (2016) and were not present at the Pellston Workshop® in this task force: Jane Bare, Markus Berger, Michael J. Lathuillière, Alessandro Manzardo, Manuele Margni, Montserrat Núñez, Amandine Valerie Pastor, Bradley Ridoutt, Taikan Oki, and Sebastian Worbe. Additionally, the contributions of Rolf Frischknecht and Olivier Jolliet are highly appreciated.

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5.12 Appendix to Part 1: Calculation of different weighted averaged CF

The equations that define the different types of factors are presented below.

1. **CF_ws,m: the equation for CF_ws,m is defined in section 1.1.4**
2. **$CF\_agri_{ws,y}$ and $CF\_non\text{-}agri_{ws,y}$:**

$$CF\_agri_{ws,y} = \frac{1}{C\_agr_{ws,y}} \sum_{m=1}^{12} CF_{ws,m} \cdot C\_agr_{ws,m}$$

$$CF\_non\_agri_{ws,y} = \frac{1}{C\_non\_agr_{ws,y}} \sum_{m=1}^{12} CF_{ws,m} \cdot C\_non\_agr_{ws,m}$$

where:

- $CF\_agri_{ws,y}$ = CF resolved at the spatial scale (watersheds), but aggregated over time and weighted by agricultural water consumption;
- $CF\_non\_agri_{ws,y}$ = CF resolved at the spatial scale (watersheds), but aggregated over time and weighted by non-agricultural water consumption;
- $C\_agri_{ws,y}$ = agricultural water consumption occurring in a year in watershed ws;
- $C\_non\_agri_{ws,y}$ = non-agricultural water consumption occurring in a year in watershed ws;
- $CF_{ws,m}$ = watershed and month-specific characterization factor;
- $C\_agri_{ws,m}$ = agricultural water consumption in month m (e.g., January) in watershed ws;
- $C\_non\text{-}agri_{ws,m}$ = non-agricultural water consumption in month m (e.g., January) in watershed ws;

3. **$CF\_agri_{c,m}$; $CF\_non\text{-}agri_{c,m}$:**

$$CF\_agri_{c,m} = \frac{1}{C\_agr_{c,m}} \sum_{ws=1}^{n} CF_{ws,m} \cdot C\_agr_{ws,m}$$

$$CF\_non\_agri_{c,m} = \frac{1}{C\_non\_agr_{c,m}} \sum_{ws=1}^{12} CF_{ws,m} \cdot C\_non\_agr_{ws,m}$$

where:

- $CF\_agri_{c,m}$ = CF resolved at the temporal scale (months), but aggregated over space and weighted by agricultural consumption;
- CF_non-agric,m = CF resolved at the temporal scale (months), but aggregated over space and weighted by non-agricultural consumption;
- C_agric,m = agricultural water consumption in month m in country c;
- C_agriws,m = agricultural water consumption in month m in watershed ws;
- CFws,m = characterization factor watershed and month specific;
- C_non-agric,m = non-agricultural water consumption in month m in country c;
- C_non-agriws,m = non-agricultural water consumption in month m in watershed ws.

4. $CF\_agri_{c,y}$; $CF\_non\text{-}agri_{c,y}$:

$$CF\_agri_{c,y} = \frac{1}{C\_agr_{c,y}} \sum_{m=1}^{12} CF\_agri_{c,m} \cdot C\_agr_{c,m}$$

$$CF\_non\_agri_{c,y} = \frac{1}{C\_non\_agr_{c,y}} \sum_{m=1}^{12} CF\_non\_agri_{c,m} \cdot C\_non\_agr_{c,m}$$

where:

- C_agric,m = agricultural water consumption in month m in country c;
- C_non-agric,m = non-agricultural water consumption in month m in country c;
- C_agric,y = agricultural water consumption in a year in country c;
- C_non-agric,y = non-agricultural water consumption in a year in country c.

5. $CF\_default_{c,y}$:

$$CF\_default_{c,m} = \frac{1}{C\_tot_{c,m}} \sum_{ws=1}^{n} CF_{ws,m} \cdot C\_tot_{ws,m}$$

$$CF\_default_{c,y} = \frac{1}{C\_tot_{c,y}} \sum_{m=1}^{12} CF_{\_default\_c,m} \cdot C\_tot_{c,m}$$

where:

- CF_defaultc,m = month-specific country weighted average default factor, weighted by total consumption over space, for month m;
- CF_defaultc,y = year-specific country weighted average default factor, weighted by total consumption over space and time;
- C_totc,m = total water consumption (both agri and non-agri) in month m in country c;
- C_totws,m= total water consumption occurring (both agri and non-agri) in month m in watershed ws;
- C_totc,y= total water consumption (both agri and non-agri) occurring within a year in country c;

6. $CF\_default_{g,y}$:

$$CF\_default_{g,m} = \frac{1}{C\_tot_{g,m}} \sum_{ws=1}^{n} CF_{ws,m} \cdot C\_tot_{ws,m}$$

$$CF\_default_{g,y} = \frac{1}{C\_tot_{g,y}} \sum_{m=1}^{12} CF_{\_default\_g,m} \cdot C\_tot_{g,m}$$

where:

- $CF\_default_{g,y}$ = global weighted average default factor, weighted by total consumption over space and time;
- $CF\_default_{g,m}$ = month-specific global weighted average default factor, weighted by total consumption over space;
- $C\_tot_{c,y}$= total water consumption (both agri and non-agri) occurring within a year in the globe.

PART B: HUMAN HEALTH EFFECTS

5.13 Scope

Water use may cause a variety of potential human health impacts through different impact pathways as depicted in a previous study (Figure 1: Kounina et al. 2013). There are generally three main types of water use for human needs: domestic, agricultural, and industrial use. The lack of water for human needs may lead to human health damages for those uses that are essential, mainly domestic and agricultural uses (Kounina et al. 2013; Forouzanfar et al. 2015) .

Water deprivation for domestic use may increase the risks of intake of low quality water or lack of water for hygienic purposes, and consequently may result in the increase of damages from infectious diseases, such as diarrhea.

Water demands in agriculture (irrigation) and fisheries or aquaculture are usually essential water needs for human nutrition in many areas of the world. In this context, deficit of water in agriculture and fisheries or aquaculture may decrease food production, and consequently result in the increase of malnutrition damage due to the shortage of food supply.

Previous publications covering these issues were considered as a starting point for this discussion: i) Pfister et al. (2009), Boulay et al. (2011) and Motoshita et al. (2014) regarding agricultural water scarcity, and ii) Boulay et al. (2011) and Motoshita et al. (2011) regarding domestic water scarcity. Moreover, preliminary steps towards harmonization were performed as part of the WULCA (Water Use in LCA) mandate and the different models and modeling choices were analyzed in detail by Boulay et al. (2015a), identifying the significant differences of the methodological concepts of the characterization factors.

A group of experts was consulted in 2015 to answer several questions that appeared during the testing of the existing methods. The debate about these questions resulted in the following conclusions:

- Differentiating between groundwater and surface water, as well as separation between different water quality classes would be nice to have, but likely not feasible with a reasonable amount of effort. Further work on possible double counting of e.g., the effects of health impacts from toxic emissions and inclusion of human health impacts associated with lower water availability due to decrease of water quality should be performed.
- It was deemed important to assess the trade of agricultural products when quantifying food supply shortage due to agricultural water deprivation.
- Regarding human health impacts of domestic water deprivation, no clear preference was provided on any of the existing approaches.
- It was suggested to consider the adaptation capacity and assess it based on an indicator derived from Gross Domestic Product (GDP), Gross National Income (GNI), or Human Health Index (HDI), with no clear preference stated.

5.14 Impact pathway and review of approaches and indicators

5.14.1 Domestic water scarcity

Two models have been developed to assess the potential human health impacts through spread of infectious diseases by water consumption: Motoshita et al. (2011) and Boulay et al. (2011). The cause-effect chain is modeled such that any water consumption in a watershed may cause deprivation based on local scarcity and incapacity to adapt economically, leading to a lack of water for domestic users and consequently impacts of reduced domestic water on human health. The equation of characterization factors in both models can be generalized as follows.

$$CF_{domestic} = SI \times DAU_{domestic} \times SEE_{domestic} \qquad \text{(Eq. 1)}$$

where:

- $CF_{domestic}$ is the characterization factor of domestic water use [DALY/m^3];
- SI is a scarcity or stress index [-];
- $DAU_{domestic}$ is the fraction of water consumed by domestic users (Distribution of Affected Users: DAU,) [-];
- $SEE_{domestic}$ is the socio-economic effect factor of domestic water use [DALY/m^3].

A method comparison was performed in a previous study to understand the consistency between the models and uncertainty due to model choices (Boulay et al. 2015). Rank correlation coefficients (RCC) and mean difference coefficients (MDC) were calculated for the set of SEE factors from the previous models.

According to the results of the method comparison, high correlation between overall SEE factors from different methods for domestic water scarcity could be found; however, detailed sensitivity analysis of parameters in SEE factors would be necessary to identify influential factors in the modeling. 5.14.2 Agricultural water deprivation

Previous analysis done by Boulay et al. (2015a) showed that potential health damages due to aquaculture or fisheries water deprivation are insignificant compared with irrigation deprivation. Thus, human health damages related to aquaculture water deprivation was not further evaluated.

Regarding the malnutrition impacts due to agricultural irrigation deprivation, three models have been developed: Pfister et al. (2009), Boulay et al. (2011) and Motoshita et al. (2014). The cause-effect chain starts from any water consumption in a watershed, quantifies the lack of water for agricultural users, and consequently quantifies the impacts of reduced food production, considering local scarcity and economic adaptation capacity. Reduced food production might directly influence domestic food availability on the one hand, and have an impact on the world market on the other hand. The impact on the world market may indirectly affect people in other countries through trade effects. Both pathways may lead to malnutrition and consequently human health impacts. The equation of characterization factors (CF) in these three models can be generalized as follows.

$$CF_{agricultural} = SI \times DAU_{agricultural} \times SEE_{malnutrition} \qquad \text{(Eq. 1)}$$

where

- $CF_{agricultural}$ is the characterization factor of water scarcity of agricultural water use [DALY/m^3];
- SI is a scarcity or stress index;
- $DAU_{agricultural}$ is the fraction of water consumed by agricultural water users [-];
- $SEE_{malnutrition}$ is the socio-economic effect factor of agricultural water use [DALY/m^3].

A sensitivity assessment of the difference between $SEE_{malnutriction}$ in the different models has been performed (Boulay et al. 2015). Distinctly different results of Motoshita et al. (2014), which includes the trade effect by allocating food deficit effects to national and international impacts, suggest that the trade effect is an important element to include in the impact assessment model.

The evaluation of the different parameters and options composing the damage indicator CF used the same criteria as those presented in the scarcity chapter. In addition, the consistency between the impact category indicator for water scarcity and the damage indicator on human health was evaluated. The analysis of the proposed methods according to these criteria are presented in Table 5.5 (next page).

5.15 Description of indicator(s) selected

The indicator for the impact pathway for agricultural water deprivation published in Motoshita et al. (2014) is modified as follows:

$$CF_{agri} = \overbrace{\underbrace{(HWC_{agri}/AMC)}_{\text{Fate}}}^{SI \times DAU_{agricultural}} \times \overbrace{\left\{ \underbrace{\underbrace{FPL \times DSR}_{\text{Exposure}} \times \underbrace{HEF}_{\text{Effect}}} + \underbrace{\underbrace{FPL \times (1-DSR) \times \sum (ISR_i}_{\text{Exposure}} \times \underbrace{HEF_i)}_{\text{Effect}}} \right\}}^{SEE_{malnutrition}}$$

Where:

- HWC_{agri} is the Human Water Consumption (HWC) in agricultural use (m^3);
- AMC is availability minus consumption, or more precisely, the water available minus human water consumption by all users (similar to the water scarcity indicator, AWARE, but not considering EWR, m^3);
- FPL is the food production losses as a result of reduced irrigation, measured in energy units (kcal / m^3);
- DSR is the domestic supply ratio of dietary energy from foods (including trade adaptation capacity, dimensionless);
- ISR_i is the import sharing ratio (including trade adaptation capacity, dimensionless) of country i;
- HEF is the health effect factor of a country where water is consumed (DALY/kcal) and
- HEF_i is the health effect factor of country i (DALY/kcal).
- All water consumption and availability data is based on WaterGAP 2.2 (Müller Schmied et al. 2014).

The determination of each indicator is described in further detail in section 5.16 below.

Table 5.5: Analysis of damage indicator parameters against selection criteria

Criteria	Fate	Effect factor			
	Withdrawal based	**Consumption based**	**SEE Local Malnutrition**	**SEE trade effect**	**SEE domestic water**
Stakeholders acceptance	Good: Applied in widely used methods	Good: Applied in widely used methods	Moderate: Applied in used methods	Low-moderate: Applied in some used methods	Low-moderate: Applied in some used methods
Main normative choice	Withdrawal is most relevant for depriving local users (local competition); AMC (availability minus consumption: actual availability) is used	Consumption is most relevant for depriving users in a watershed (watershed competition); AMC (actual availability) is used	Water deprivation on watershed level leads to reduced water availability for irrigation / link of DALYs due to protein-energy malnutrition to calorie deficit	Reduced food production in one country may affect world market and supply in other countries as a function of purchase power parity income	Water deprivation on watershed level may lead to reduced water availability for domestic use
Physical meaning	Share of water that potentially deprives other local uses [0,1]	Share of water that potentially deprives other uses within a watershed [0,1]	DALY from malnutrition / food calorie supply loss (induced by m^3 irrigation water deprivation [DALY/kcal] / [DALY/m^3]	Food calorie supply loss effects on trade per calorie loss in producer country (spatial distribution of consequence on country level) [DALY/kcal]	DALY from waterborne diseases / domestic water deprivation (induced by watershed domestic deprivation) [DALY/m3]
consistency with midpoint indicator	*Lower consistency (demand = withdrawal), ratio instead of A/AMC*	Higher consistency, *ratio instead of A/AMC*	*Not applicable*	*Not applicable*	*Not applicable*
Robustness with reference data	*Not available*	*Not available*	Underestimate impacts (mainly of reduced production in high income countries on other areas)	Improved *match with total malnutrition impacts*	*High uncertainty of cause-effect chain*

Three main aspects are adapted from Motoshita et al. (2014):

- The scarcity and DAU factors are combined in [HWC_{agri} / AMC] with monthly resolution, using CTA (Consumption to Availability) as a basis for scarcity, with availability reflecting actual availability (defined as AMC, availability minus consumption, consistently with scarcity indicator recommended), and DAU being based on the fraction of water consumed by agriculture.
- The income component of the inequality adjusted Human Development Index (I-HDI_{income}) is applied in DSR and ISR to reflect the trade adaptation capacity (whether the population will be able to purchase food at higher prices if food production decreases due to lack of irrigation), for the middle income countries. For high and low income countries, the trade adaptation capacity is set to 1 and 0 as thresholds of maximum and minimum capacity, respectively.
- HEF is taken as the average value of malnutrition damage per calorie deficiency of the undernourished population, similarly to what was done in Boulay et al. 2011, using updated data from 2013 World Health Organization (WHO) and Food and Agriculture Organization (FAO) reports.

No indicator for the impact pathway of domestic water deprivation is recommended. At this point, there are no data supporting the impact pathway that an additional water consumption and water scarcity in an area affect human health by reducing the amount of water available for domestic use, as other factors such as infrastructure, legislation, and local practices also influence the amount and quality of water consumed by domestic users. It is suggested to use one of the two previous models as analyzed in Boulay et al. (2015) for sensitivity assessments of the impacts by domestic water deprivation until further recommendations are provided.

5.16 Recommended model and specific issues addressed

The recommended fate factor HWC_{agri} / AMC (in previous publications expressed as SI x DAU) describes the effect of the consumption of 1m^3 of water in a watershed on the change of water availability for agricultural use. This factor could vary from 0 (assuming no agricultural water users in a region) to 1 (the entire volume of water consumed is depriving agricultural users). HWC_{agri} / AMC might be >1 in case agricultural water consumption exceeds the remaining water (AMC), but is limited to 1. The factor retained assumes that agriculture suffers proportional to the share of current agricultural water consumption. This could over- or underestimate the real amount of water by which agriculture will be deprived by the consumption of water in a watershed, as water rights, regulations, water markets, and specific willingness-to-pay of some users are not considered in this assumption.

FPL needs to be defined in alignment with HWC_{agri}/ AMC as defined above, based on the amount of water consumed. According to Motoshita et al. (2014), this is defined by the ratio of production amount attributable to irrigation (kcal: total crop production multiplied with the ratio of irrigation water volume to total water volume consumed for crop growth) divided by irrigation input (m^3). This was expressed as a function of water withdrawal and has now been adjusted to consumption to improve consistency with the midpoint indicator.

DSR and ISR model the effects of trade and take into account the fraction of food exports and imports, as well as the trade adaptation capacity. Countries with a high trade adaptation capacity can increase food imports (or reduce food exports) when their domestic food production decreases due to reduced water availability. This domestically reduces the lack of calories from food production loss by agricultural water deprivation, but may result in health impacts internationally by reducing food availability in other countries, leading to an increase in food prices and hence reduced ability to import by some countries (as described in more details in Motoshita 2014). The income-component of the inequality-adjusted Human Development Index ($I\text{-}HDI_{Income}$: United Nations Development Programme 2014) is used to represent the trade adaptation capacity for middle income, whereas low income and high income countries defined by the World Bank have the same adaptation capacity as defined in Boulay et al. (2011) and Motoshita et al. (2014), i.e., 0 and 1 respectively.

The health effect factor (HEF) is calculated based on the average DALY of protein-energy malnutrition damage (taken from GBD 2013) per food deficiency in kcal, as calculated in Boulay et al. (2011).

5.17 Characterization factors (excerpt, including qualitative and quantitative discussion of variability and uncertainty)

Characterization factors calculated at the monthly level and watershed scale were aggregated by weighting based on monthly consumption of water on annual level, and by weighting based on watershed consumption on the national level. Two types of characterization factors for agricultural water consumption and of non-agricultural water consumption are provided (Figures 5.9 and 5.10, next page), since they follow different consumption patterns over time and space (similar to the water scarcity indicator AWARE). Areas where no data are provided (NA) refer to areas where no significant irrigation takes place in the hydrological model that is used as the basis of water availability and demand calculation in this model. Hence, the model does not predict deprivation of agricultural users in this region. These characterization factors are available for download from http://www.lifecycleinitiative.org/applying-lca/lcia-cf.

CFs for the elementary flows of agricultural water consumption are generally larger than those for non-agricultural water consumption because scarcity

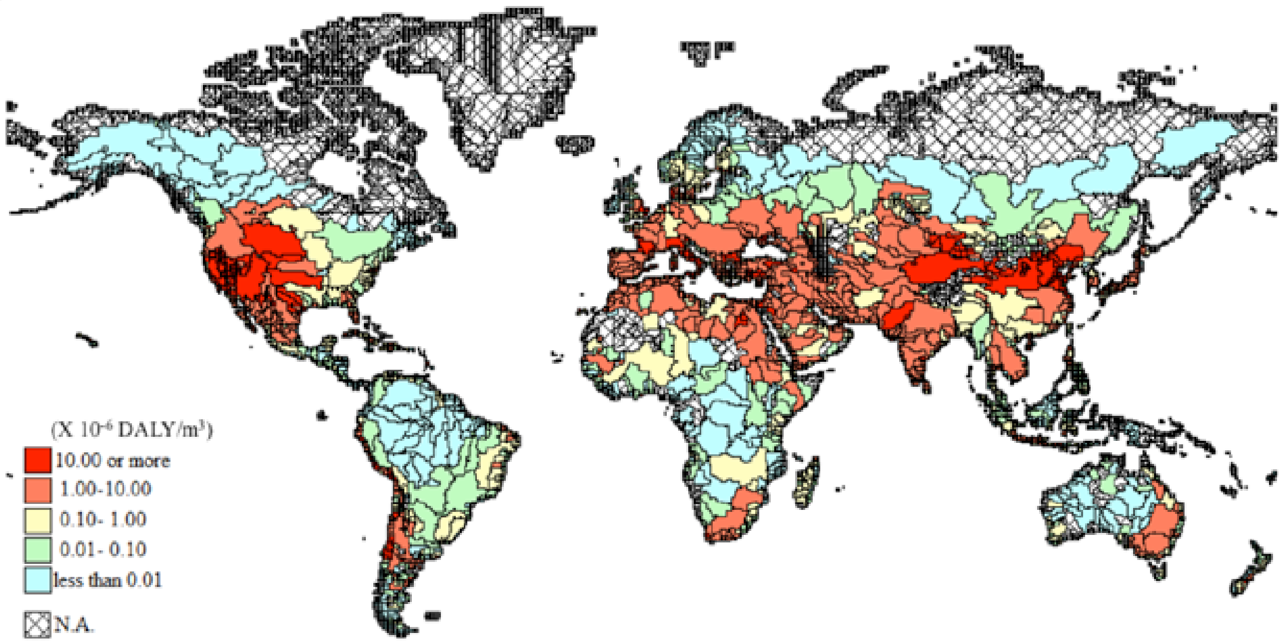

Figure 5.9: CFs for elementary flows of agricultural water consumption

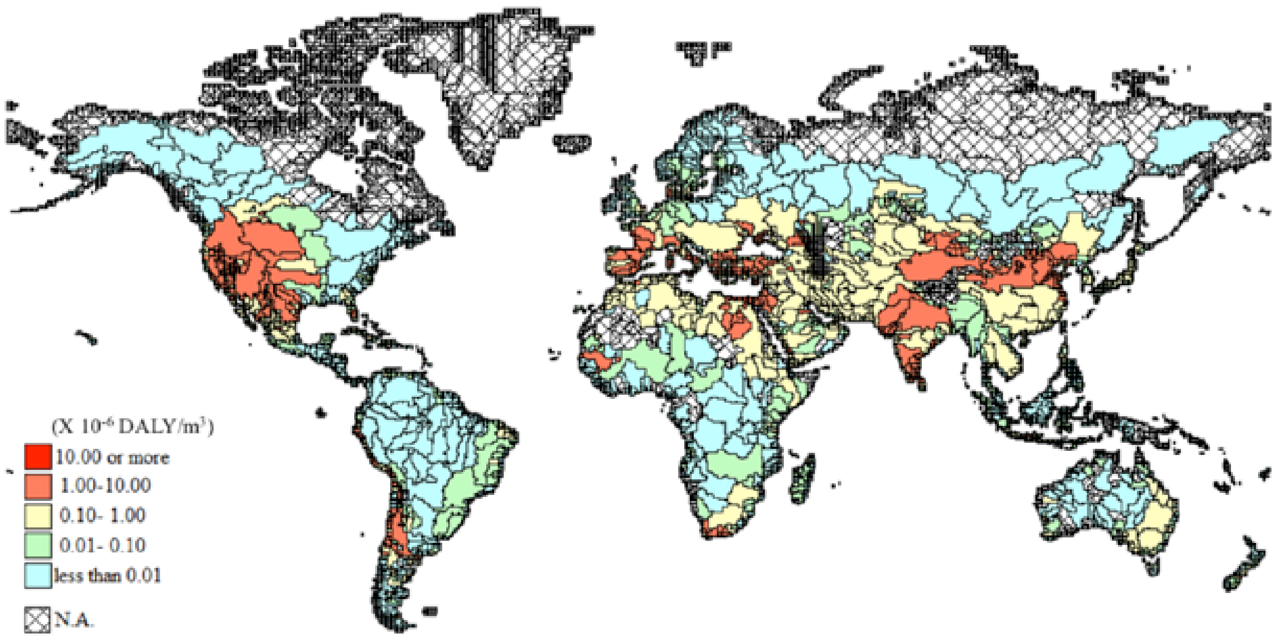

Figure 5.10: CFs for elementary flows of non-agricultural water consumption

is usually higher in regions where irrigation is required.

The aggregation from monthly values to annual average values removes a temporal variance. The ratio of the weighted annual average to monthly values of the scarcity index ranges from 0.15 to 3.46. This means CFs implicitly contain a temporal variance from 0.15 to 3.46. Socio-economic effect (SEE) factors are calculated based on annual data, and consequently temporal variances attributed to SEE factors are not quantitatively determined.

Regarding spatial variance, CFs range from 0 - $4.4 \cdot 10^{-5}$ [DALY/m^3] (the lower quartile: $4.3 \cdot 10^{-8}$, median: $8.6 \cdot 10^{-7}$, the upper quartile: $3.5 \cdot 10^{-6}$) for elementary flows of agricultural water consumption and from 0 - $2.20 \cdot 10^{-5}$ [DALY/m^3] (the lower quartile: $1.1 \cdot 10^{-8}$, median: $2.4 \cdot 10^{-7}$, the upper quartile: $1.3 \cdot 10^{-6}$) for elementary flows of non-agricultural water consumption. The health effect factor is determined as the geometric mean value of protein-energy malnutrition damage per calorie deficit for all available countries. While protein-energy malnutrition damage per calorie deficit may differ among countries, no reasonable justification could be found to explain the large variance and outlier countries except the generally low quality of estimating malnutrition and DALY from malnutrition. Additionally, there is discrepancy of data sources for protein-energy malnutrition damage and calorie in deficit (depth of hunger), since they are assessed by different sources. Previous analyses revealed that regional malnutrition damage per case varied by a factor of 2.0 (95% confidence interval), when comparing WHO world regions (Pfister and Hellweg 2011). Additionally, Boulay et al. (2011) analyzed the variance of malnutrition damage per calorie in deficit across countries (geometric standard deviation: 2.43). Therefore, we suggest adopting a geometric standard deviation of 2.0 for sensitivity analysis of CFs in terms of variance of health effect factor.

The CFs for representative countries are shown in Table 5.6. Germany, as an example of developed countries, has no impact of national damage, but high trade-induced damage. Columbia, as an example of average countries, has higher impacts of both national and trade-induced damage than those of Germany. Mozambique, as an example of developing countries, has the highest impacts of both national and trade-induced damage among representative countries in the table. These examples typically express that countries with high economic adaptation capacity can avoid health damages through global trade while trade-induced damage occurs in other food importer countries.

This method assesses potential malnutrition impacts from a reduction in food availability due to a decrease in food production of current agricultural water users, which was caused by a shortage of water for irrigation induced by the increase of water consumption in the system under study. However, when that system is actually a food-producing system, such a reduction in food availability does not occur to the same extent as the assessed decrease in food production, or at all. The net reduction of food availability in the system depends on: 1) the difference in water use efficiency of the two different food-production systems, the previous one and the new one, in kcal/m^3, and 2) the intended use of the crop (animal feed for meat production or direct consumption, for example). If this method is used for the assessment of food producing systems, the functional unit might compensate the calculated potential impact on human health, and therefore results should be interpreted carefully.

5.18 Rice case study application

The rice case study is presented in detail in Chapter 3. Water consumption in all three situations is highly dominated by the rice cultivation phase (more than 99.4%), and therefore the other production stages have been neglected in this analysis. The case study for rice production in the USA is having the lowest water consumption, followed by the one in China (Table 5.7, next page).

The national average characterization factors of water consumption (agri) are similar for USA and China, while the CF (agri) of water consumption in India is 50% lower. As a result, the LCIA results reflect the inventory results for the comparison of the USA-Switzerland and urban China case, while the rural

Table 5.6: Examples of the CFs for representative countries

		CFs for agricultural water consumption [DALY/m^3]	CFs for non-agricultural water consumption [DALY/m^3]		
		National damage	Trade-induced damage	National damage	Trade-induced damage
Developed country	Germany	0	$7.20 \cdot 10^{-7}$	0	$7.90 \cdot 10^{-8}$
Middle income country	Columbia	$4.49 \cdot 10^{-8}$	$1.00 \cdot 10^{-7}$	$7.31 \cdot 10^{-9}$	$1.85 \cdot 10^{-8}$
Developing country	Mozambique	$4.08 \cdot 10^{-7}$	$5.34 \cdot 10^{-7}$	$1.65 \cdot 10^{-7}$	$2.49 \cdot 10^{-7}$

Table 5.7: Results of the rice case studies for 1 kg of white rice cooked

	Inventory		CF_{agri} (DALY/m³)			Impact (DALY)		
Case	Water consumption (m³) in rice production (share of total in %)	Watershed	CF (National)	CF (Trade-Induced)	CF (Total)	National damage	Trade-induced damage	Total damage
			[DALY/m³]	[DALY/m³]	[DALY/m³]	[DALY]	[DALY]	[DALY]
Rural India	0.78 (99.9%)	Average	1.8E-06	1.8E-06	3.6E-06	1.4E-06	1.4E-06	2.8E-06
		Ganges	2.1E-07	2.1E-07	4.1E-07	1.6E-07	1.6E-07	3.2E-07
		Godavari	9.7E-07	9.6E-07	1.9E-06	7.6E-07	7.5E-07	1.5E-06
Urban China	0.46 (99.5%)	Average	3.5E-06	3.2E-06	6.7E-06	1.6E-06	1.5E-06	3.1E-06
		Yellow River	9.2E-06	8.3E-06	1.8E-05	4.3E-06	3.8E-06	8.1E-06
		Pearl River	1.7E-07	1.6E-07	3.3E-07	8.0E-08	7.2E-08	1.5E-07
USA-Switzerland	0.08 (99.4%)	Average	0.0E+00	7.0E-06	7.0E-06	0.0E+00	5.6E-07	5.6E-07
		Red River	0.0E+00	4.6E-07	4.6E-07	0.0E+00	3.7E-08	3.7E-08
		Arkansas River	0.0E+00	4.6E-07	4.6E-07	0.0E+00	3.7E-08	3.7E-08

India case results in lower impacts than urban China. While for China and India the human health impacts are almost equally shared between local population and through trade, the water consumption of US rice production exclusively causes human health impacts on global population through trade.

As mentioned in Part A of this chapter, national average CFs are not satisfactory for foreground systems, and watershed-specific and time-specific CFs should be applied. As the rice production time schedule is not necessarily fixed to one period, we only focused on spatial specification and further differentiated the rice production locations in each country. For this purpose, we selected two major watersheds where rice is produced within each country: Ganges (case study location) and Godavari in India; Yellow River and Pearl river (case study location) in China; and Red river and Arkansas river in the US (both within case study area) (see Table 5.4).

In the case of India and the US, both major watersheds have lower characterization factors than the national average. In the case of the US, where rice production is restricted to a small area around the state of Arkansas, the CF is 15 times lower than the US average. In the Ganges, CF is almost 10 times lower than the average, and the CF of the Godavari River is still 50% lower than average. In China, the selected case of the Yellow River has much higher CF than in the other cases and therefore results the highest impacts per kg of rice consumed. As a limitation of this analysis, it needs to be noted that changes in the life cycle inventory of rice cultivation as a function of the production site have not been considered.

5.19 Recommendations and outlook

5.19.1 Main recommendation

The group agreed on recommending the CF for the impact pathway describing agricultural water deprivation and consequences on human health. These characterization factors are available for download from http://www.lifecycleinitiative.org/applying-lca/lcia-cf. Caution is required for interpreting results for food-producing systems. A minority was reluctant to recommend this method for food-producing systems.

The group suggests not excluding the possibility of modeling the impacts associated with domestic water scarcity. However, given the level of current understanding, there is not sufficient evidence to recommend a specific methodology, where evidence refers to causality between water consumption, scarcity, and domestic water deprivation causing water-related diseases. Further research is needed and envisaged steps are indicated in the roadmap described below.

5.19.2 Judgment on quality, interim versus recommended status of the factors and recommendation

The characterization factors for the impact pathway describing agricultural water deprivation and consequences on human health are recommended for application with special attention to the interpretation of food-producing systems.

5.19.3 Applicability, maturity and good practice for factors application

The recommended model and characterization factors are applicable to life cycle inventory datasets quantifying water consumption. The method is applicable at the scale and time resolution, which can be typically found in background inventory (country, global, year) as well as at highly resolved geographic scales and time resolution (watershed and month). Use of global CF is not recommended. The characterization factors provided together with this publication are recommended for applications to the assessment of marginal changes in water consumption only. If this method is used for the assessment of food-producing systems, only the decrease in food availability due to water consumption of the system is considered in the impact assessment, and not the change in food availability resulting from the food it produces. If this method is used for the assessment of food-producing systems, the functional unit might compensate the calculated potential impact on human health, and therefore results should be interpreted carefully. The endpoint assessed in DALY indicates potential human health impacts and is not meant to represent real measured impacts.

5.19.4 Roadmap for additional tests

Additional refinement of the geographic scale of the adaptation capacity is recommended (e.g., sub-regional maps of GDP [PPP] per capita) to increase the robustness of the malnutrition approach.

Investigations about the robustness of the use of calorie-deficit as proxy for protein-deficit malnutrition are recommended, and more specific data on regional health responses to malnutrition should be investigated in the future.

Additional tests should aim at the assessment of the relationship between domestic water scarcity and damage associated to lack of water for domestic use. In particular, linkages between population density, income, accessibility to safe water, water scarcity, and effect factors at the watershed or country level should be investigated.

5.19.5 Next foreseen steps

Additional tests on the impact pathway associated with domestic water scarcity need to be finalized and specified.

We suggest that further work on possible double counting and the inclusion of human health impacts associated with lower water availability due to decrease of water quality be performed.

5.20 Acknowledgements

The task force acknowledges the contribution and work from the WULCA members of the human health sub-group that were not present in this task-force at the Pellston Workshop®: Jane Bare, Cecile Bulle and Bradley Ridoutt, as well as the experts who contributed to the workshop in Barcelona: Tereza Levova, Andrew Maddocks, Bo Weidema, Julie Clavreul, Camillo de Camilis, Tommie Ponsioen, and Sebastien Humbert.

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6. Land use related impacts on biodiversity [TF 5 Land use]

L. Milà i Canals, A. Antón, C. Bauer, C. de Camillis, R. Freiermuth, T. Grant, O. Michelsen, M. Stevenson

6.1 Scope

Land use and land use change are main drivers of biodiversity loss and degradation of a broad range of ecosystem services (MEA 2005). Despite substantial contributions to address land use impacts on biodiversity in LCA in the last decade (Schmidt 2008, de Baan et al. 2013a, Souza et al. 2013, Coelho and Michelsen 2014, LEAP 2015), including work coordinated by the UNEP SETAC Life Cycle Initiative (Milà i Canals et al. 2007; Koellner et al. 2013a; 2013b, Teixeira et al. 2016, Curran et al. 2016), no clear consensus exists on the use of a specific impact indicator. This lack of consensus not only limits the application of existing models, but also imposes constraints on the comparability of results of different studies evaluating land use impacts while applying different models. Therefore, the scope of this chapter is to give advice on defining a modeling approach and related indicator(s) adequately reflecting impacts of land use on biodiversity. The framework should be applicable on a local, regional, and global scale, and able to differentiate the diverse land use intensities as much as possible (Teixeira et al. 2016). Furthermore, it has to be linked with data availability in the life cycle inventory.

Regarding land use impact assessment, LCA aims to evaluate specific production techniques in land intensive activities such as agriculture or forestry, as well as to provide a perspective of the land use impacts across all stages of the products' life cycles and land use types. This kind of application requires a high level of differentiation on a local scale, for which to date no globally valid methodology is readily available.

According to the Convention on Biological Diversity (CBD, UN 1992) we understand biodiversity as the variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems (CBD, UN 1992, article 2). Biodiversity has key functions for humanity ranging from influencing our wellbeing to being a resource, but it also has an intrinsic value. Several sustainable development goals (SDG, UN 2015) are linked to biodiversity, the most explicit being goal 15 on terrestrial biodiversity, "Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss." As SDG indicators measuring the evolvement of this goal, the following are proposed, among others:

- 15.1.1. Forest area as a percentage of total land area
- 15.2.1. Forest cover under sustainable forest management
- 15.3.1. Percentage of land that is degraded over total land area
- 15.5.1. Red List Index

The term 'biodiversity' is plural and encompasses a wide range of biological features with distinct attributes (ecological composition, function, and structure), and nested into multiple levels of organization (genetic, species, population, community, and ecosystem). An ideal biodiversity indicator should adequately portray the complexity, as well as the spatial and temporal characteristics of biodiversity attributes, but at the same time it needs to be easy to measure and simple to communicate (Curran et al. 2010). Furthermore, the ideal indicator must support decision making in terms of systems comparisons.

6.2 Impact pathway and review of approaches and indicators

With the overall goal to provide a measurable and simple indicator or guidance on how to assess potential impacts due to land use on biodiversity, the land use biodiversity task force has conducted a critical review of the existing frameworks for land use impact pathway in LCA, as well as an evaluation of existing models in and outside the field of LCA, in order to identify models of particular promise to be recommended (Curran et al. 2016).

6.2.1 Impact pathway

From inventory flows (land use interventions) to endpoint (biodiversity change), there is a very complex pathway with several interconnections, including impacts on habitat structure. Figure 6.1 summarizes the current agreement on the conceptual model of impact pathway for potential impacts of land use on biodiversity, moving from land interventions (occupation and transformation) to resulting environmental pressures and impacts at the level of impact categories and endpoints (the latter aggregated to damage categories, see Chapter 2). Because of the complexity of the pathway, simplifications are needed and it must be acknowledged that not all aspects may be included in a single indicator. Nevertheless, consensus has been achieved in the need to represent biodiversity damage, including species and ecosystem features at local and regional levels.

6.2.2 Review of approaches and indicators

In order to provide an overview of cutting-edge impact assessment approaches and methods relevant for the Pellston Workshop®, the Biodiversity Land Use Task Force identified 73 publications in the literature, 31 out of the 73 publications matched the criteria for method documentation and were found suitable for characterization. The documentation criteria used in the selection were the following: 1) the main description of the model was required to be published in a peer-reviewed scientific journal, and 2) models should enable characterization of impacts on biodiversity in at least two different land use or cover classes or intensities of generic land use archetypes (e.g., forest or agriculture, intensive or extensive). Among the 31 methods that passed the selection (see Curran et al. 2016), 20 were developed specifically for environmental impact assessment in LCA and 11 were proposed from non-LCA domains (environmental policy, ecology, and conservation).

To evaluate these methods, criteria based on the approach used by the European Commission within the International Reference Life Cycle Data System (ILCD), on the evaluation of LCIA models and indicators (EU-JRC 2011) were adopted. The Biodiversity Land Use Task Force grouped sets of evaluation criteria under the following categories: (i) "Completeness of scope;" (ii) "Biodiversity representation;" (iii) "Impact pathway coverage;" (iv) "Scientific quality;" (v) "Model transparency and applicability;" and (vi) "Stakeholders acceptance." A set of specific criteria was developed for each evaluation category and the degree to which each model fulfilled each criterion was qualitatively described. For each model, we first summarized the main model characteristics, including the indicator(s) used to represent biodiversity, their position on the cause-effect chain (impact pathways) leading from land use interventions to biodiversity loss, as well as the underlying data upon which each model was based (e.g., literature data, expert opinion, Habitat Suitability Models, Species Distribution Models).

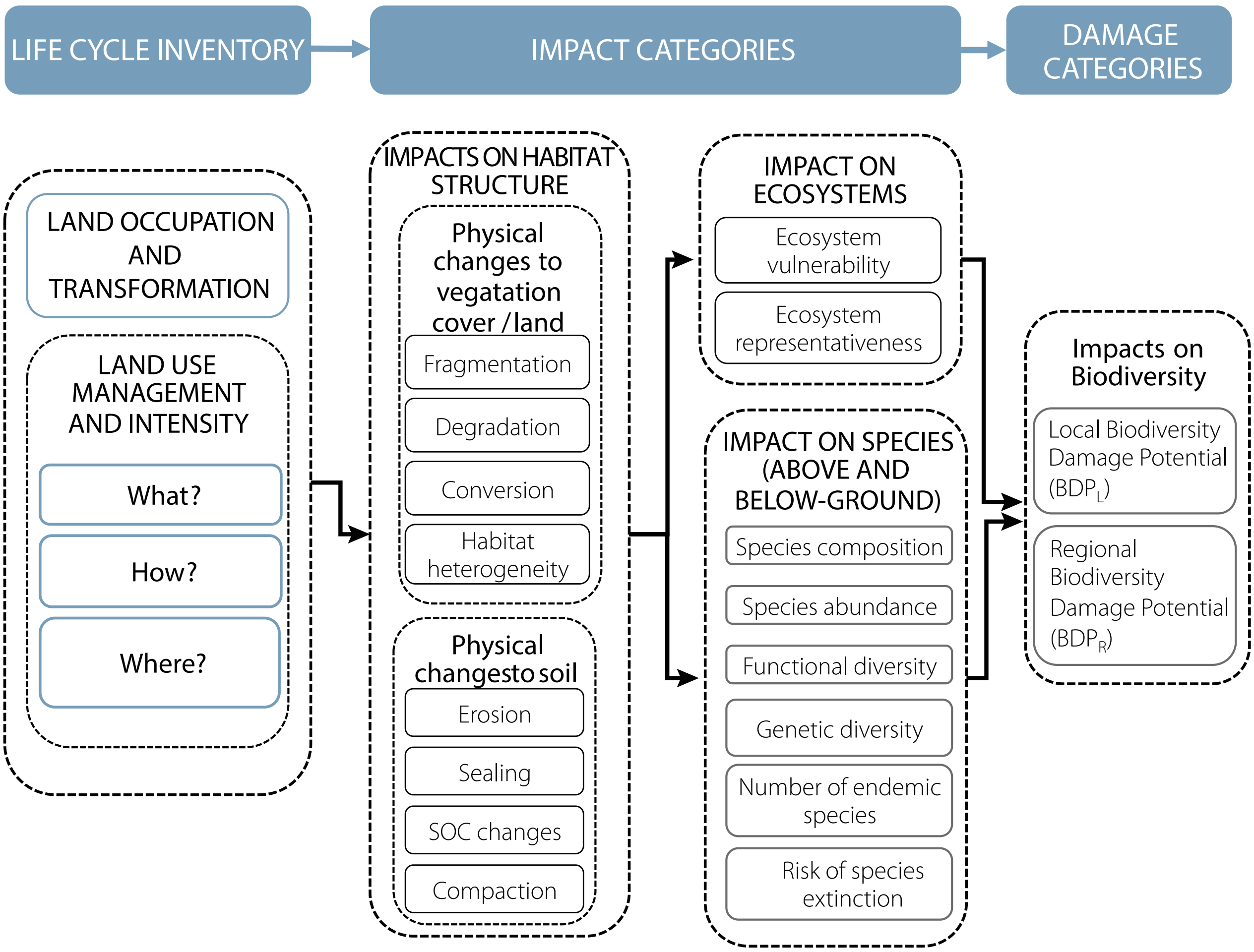

Figure 6.1: Impact pathway model (Adapted from Curran et al. 2016)

Curran et al. (2016) provide a detailed and comprehensive evaluation of the 31 methods reviewed. As a summary of results we conclude that the most common pathway assessed was the direct, local degradation and conversion of habitats. Regarding biodiversity representation, most of the current models are based on compositional aspects of biodiversity, namely species richness followed by species abundance. Different spatial scales of assessment have been used, being ecoregion the one with the highest potential for consensus. Presently, it is difficult to get data on both biodiversity and the geographic location of activities to enable a more granular scale. Several taxonomic groups are covered by distinct models, plants being the most common taxon assessed across models. Measures of habitat quality are largely subjective in nature, and include the "naturalness" of land cover classes (i.e., "Hemeroby" scores [Brentrup et al. 2002]). At the regional scale, indicators of the overall species pool size were most common, followed by habitat quality and extinction risk.

Species-Area Relationship (SAR) describes the dependency of species richness with the amount of land use (Milà i Canals and de Baan 2015). The classic SAR model has been criticized because of its assumption that all natural area converted to human-dominated areas becomes completely hostile to biodiversity; Matrix SAR offered improvements to the Classic SAR, but still predicts 100% species loss if no natural habitat remains within a region. The Countryside SAR model has been suggested as superior to the aforementioned SARs because it accounts for the differential use of habitats by species and predicts that species adapted to human-modified habitats also survive in the absence of their natural habitat (Chaudhary et al. 2015).

The reference state is relevant at both the local scale as a benchmark habitat to standardize land use comparisons; and at the regional scale as a baseline for calculating weighting factors (e.g., degree converted) and future scenarios of land use change. At the local scale, a potential natural vegetation (PNV) was (often implicitly) assumed as the reference state. At the regional scale, the use of both PNV and current state was equally frequent. Regional weighting factors using degree of conversion, scarcity or rarity, or summed hemeroby or abundance values implicitly apply a PNV reference.

As a conclusion of the review performed, the land use task force agreed on the need of inclusion of both local and regional or global impact on biodiversity. The local impact component puts the main focus on what and how an activity is performed, while the regional or global impact component puts the main focus on where an activity is performed. These are not mutually exclusive and both should be included. In addition, the task force concluded, a good indicator should include weighting factors associated to the habitat vulnerability of specific regions.

6.3. Criteria applied and process to select the indicator(s)

In order to be able to recommend a method, several tasks were fulfilled. These included an intensive exchange with experts outside of the task force, a comprehensive analysis of existing models, the test of applicability within a case study (see section 6.7), and finally the exchange with method developers during the Pellston Workshop®. These four steps are described in detail below:

1) Two workshops in San Francisco and Brussels with a total of 38 domain experts revealed the importance of considering different geographical levels, the state of the ecosystems at the assessed location, and the land use intensity levels. Species richness was discerned as practical proxy for assessing biodiversity. Special attention was given on how results are to be communicated. A third workshop in Brazil highlighted the stakeholders' sensitivity in choosing a reference state (Teixeira et al. 2016).

The experts who participated in the expert workshops stressed the importance of the framework established by the Life Cycle Initiative, appreciating the early engagement of stakeholders in the consensus-building process. Experts agreed that LCA should go beyond inventory data for land use and land use change (LU/LUC), and relate elementary flows to their respective impacts on biodiversity, while paying attention on how final results of LCA studies are communicated. Moreover, there was also an agreement that a good LCA indicator for biodiversity necessarily has to consider geographical location, several aspects that depict the state of ecosystems at that location, and a measure of land use intensity. Species richness was considered a good starting point for assessing biodiversity loss. However, complementary metrics need to be considered in modeling, such as habitat configuration, inclusion of fragmentation and vulnerability (Teixeira et al. 2016).

2) An evaluation of existing methods was then conducted following the stepwise procedure illustrated in Section 6.2, and published in Curran et al. (2016).

3) Among the different methods evaluated and based on the conclusions of expert workshops conducted, the land use biodiversity task force decided to test those suited to provide global CFs for a case study (see section 6.7).

4) Based on the tasks conducted previously and the existence of global coverage CFs, two methods discussed in the Pellston Workshop®. These were Coelho and Michelsen (2014) and Chaudhary et al. (2015). The recommendation of a model including characterization factors and application areas during the Pellston Workshop® built mainly on these two methods.

6.4. Description of indicator(s) selected

The indicator selected is the potential species loss (PSL) from land use based on the method described by Chaudhary et al. (2015). The indicator represents regional species loss taking into account the effect of land occupation displacing entirely or reducing the species that would otherwise exist on that land, the relative abundance of those species within the ecoregion, and the overall global threat level for the affected species. The indicator can be applied both as a regional indicator (PSLreg), where changes in relative species abundance within the ecoregion is included, and as a global indicator (PSLglo) where also the threat level of the species on a global scale is included (see section 6.5).

The indicator covers five taxonomic groups; birds, mammals, reptiles, amphibians, and vascular plants. The taxonomic groups can be analyzed separately or can be aggregated to represent the potentially disappeared fraction (PDF) of species. Land use types covered by the method include intensive forestry, extensive forestry, annual crops, permanent crops, pasture, and urban land. The reference state is a current natural or close to natural habitat in the studied ecoregion. The model provides characterization factors down to 804 ecoregions based on Olson et al. (2001), as well as country level and global average characterization factors. The characterization factors are provided by taxon for both land occupation in global species eq. lost/m^2 and land transformation in global species eq. lost × year/m^2, or aggregated across taxa as global PDF/m^2 and land transformation in global PDF × year/m^2. The model includes both average and marginal factors.

The indicator does not explicitly include biodiversity impacts connected to changes in ecological structure, nor does it include shape or fragmentation effects. However, the species loss would implicitly represent changes in ecological structure in some facets. The indicator is currently limited to six land use types and while these are possibly the most relevant land uses, the current indicator has poor resolution when it comes to alternative management practices within them.

6.5. Model and method

The impact model developed by Chaudhary et al. (2015) builds on a prior model by de Baan et al. (2013) with significant updating to input data and innovations to the model. The model contains an impact pathway, which includes three levels of concern relative to biodiversity conservation values. Figure 6.2 provides an overview of the impact model used to calculate the two impact categories PSLreg and PSLglo. It begins with land occupation under different land use types and compares the local species diversity of each land use type to an undisturbed habitat. At the level of ecoregions, the model looks at the regional significance of this species loss. Finally, it estimates the global vulnerability of the species, expressed as number of threatened endemic species divided by total species richness hosted by the ecoregion, to determine the global potential impacts on biodiversity for land occupation.

Land transformation is treated the same as land occupation after multiplying the area by the regeneration time divided by 2; this assumption of full recovery deserves further attention in future developments. Unlike regional impacts pertaining to species loss within ecoregions, global impacts are those resulting on a permanent global (irreversible) species loss.

The formula for calculation of the characterization factor for local species loss (CF_{loc} , dimensionless) is a function of the ratio of species richness between each land use and reference state and this is calculated

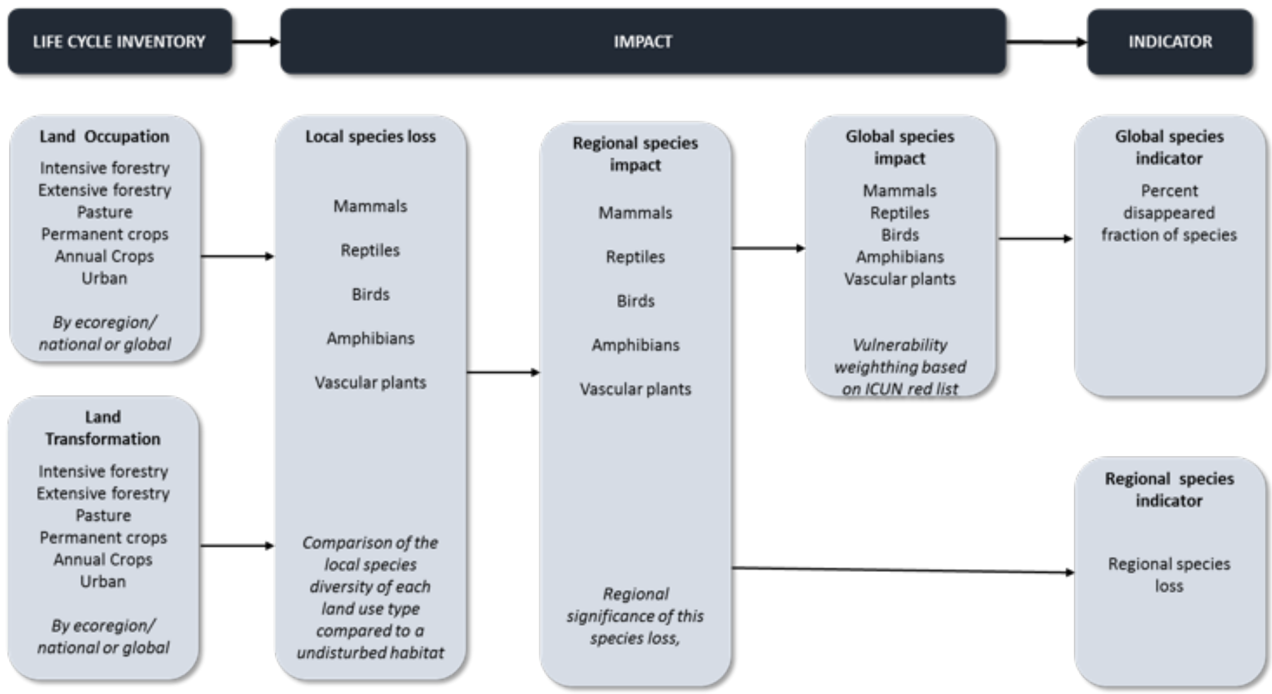

Figure 6.2: Schematic of the model used for calculation of recommended indicators.

Inventory flows for land occupation will be expressed as m^2·years (area and time land is occupied for a given product or activity) and m^2 (transformed area, amount of land use change per product or activity) for land transformation. Inventory data should be collected for each specific land use type and specific geographical unit: ecoregion, nation or global.

for the six land use types, five taxa, and biome level4 The data are sourced from plot-scale biodiversity monitoring surveys which were obtained from over 200 publications giving more than 1000 data points. The regional and global CF were then calculated on ecoregion level.

Regional species loss is calculated using species area relationships for each land use type - referred to as the Countryside SAR model. The species loss is a function of the original species richness multiplied by the species loss in the region due to the land use. This species loss is calculated as the ratio of the natural area remaining after land use compared with the original natural area (with an adjustment for the species richness of the land use type).

The regional characterization factors (CF_{reg}) are aggregated to provide a single value for potential species loss from land use - regional (PSLreg) using equal weighting for each of the five taxa. Future work could look at the effect of different weightings in different taxa or functional position of different species in the ecosystems.

If the species are endemic to the ecoregion, their loss will translate into global species loss (extinction). To determine an estimate of the permanent global (irreversible) species loss, the regional CFs for each taxon and ecoregion are multiplied by a vulnerability score (VS) of that taxon in that ecoregion. The VS is based on the proportion of endemic species in an ecoregion and the threat level assigned by the IUCN red list for the different taxa and regions.

The proportion of endemic species in an ecoregion is expressed as the ratio of area (km^2) for each species inside the ecoregion and the total (global) geographic area (km^2) coverage of this species and then aggregated for total number of species of taxa found within the ecoregion. The endemic richness of a region can be interpreted as the specific contribution of the region to global biodiversity. The threat level is obtained by a linear rescaling of the IUCN red list to 0.2 representing the least concern 0.4 near threatened, 0.6 vulnerable, 0.8 endangered, and 1 representing critically endangered.

Then the final CFs (CFglo) for the taxa included in this step (vascular plants, birds, mammals, reptiles, and amphibians) are obtained by multiplying the CFreg for each species by the calculated VS. The global threat level of vascular plants are not well characterized in the IUCN red list so they were not included in the

4 There were not enough datapoints to derive the CF(local) on ecoregion level - they were instead quantified on a biome level.

global indicator published in Chaudhary et al. (2015). However, authors recently published an updated version with CFglo including vascular plants, which may be downloaded from the LC-Impact webpage http://www.lc-impact.eu/.

In order to provide an aggregated CF, the different CFglo are divided by the total species diversity threat for each taxon and are then combined into a single score averaging the animal PDFs (with equal weighting) and then again averaging animal and plant PDF (with equal weighting). Such aggregated CFs for potential species loss from land use globally are measured in percent global potentially disappeared fraction of species (PDF).

All the above relate to the impact of land occupation. The current approach to determine the impacts of land transformation is to take the regeneration time of each land use type to return to the reference state into account following Curran et al.(2014), and multiply the occupation impact by ½ the reference time, as suggested in Milà i Canals et al. (2007). This approach is simplistic as linear recovery is assumed and refinement would be beneficial

The reference state used in the model is referred to as natural undisturbed habitat which could be seen as synonymous with potential natural vegetation PNV. In practice this comparison was done on pair pieces of land within close vicinity when one piece of land was undisturbed and the other was being used for one of the classified land use types. The purpose of this reference state is to provide a common reference against which one can estimate the additional damaging effects on nature caused by the studied land use (Milà i Canals et al. 2007), and not to suggest that LCA aims to allow land to evolve to potential natural vegetation.

In addition to the reference state used to approximate the magnitude of the potential local impact of the land use, two additional characteristics of biodiversity are considered in the model as explained above. First, the local species presence results are compared against the species' distribution throughout the ecoregion, using GIS distribution of each species in each ecoregion in the recent years. Then, the threat level of species (based on the IUCN red list, also based on the recent past) is used to weigh the regional CF with the vulnerability of each taxon in each ecoregion.

For a full and detailed explanation of the calculations and equations we address the reader to the original paper of Chaudhary et al.(2015).

6.6. Characterization factors (excerpt, including qualitative and quantitative discussion of variability and uncertainty)

6.6.1 Description and Recommendations Based on Current Model

As described, the method covers land occupation and land transformation of six different land use types[5]: annual crops, permanent crops, pasture, urban, extensive forestry, and intensive forestry[6]. Each given land use type can be characterized as a global average, for a country, and for a given ecoregion. The characterization factors are provided in global PDF/m^2 (for occupation) and global PDF × year/m^2 (for transformation) as median and lower/upper 95% percentile. We strongly recommended using ecoregions for processes in the foreground system rather than country averages.

Characterization factors have been calculated for both regional and global aggregated, and for both average and marginal situations (Chaudhary, 2015 pp 160ff; Chaudhary et al. 2015) (see global average values as example in Table 6.1). Our recommendation is to use the average factors (and not marginal) for consistency with other indicator methods used in LCA. These characterization factors are available for download from http://www.lifecycleinitiative.org/applying-LCA/LCIA-CF. However, if it is known that the system in focus causes significant land expansion, we recommend considering marginal values.

As the regional CFs are an intermediary step in developing the global aggregates and do not include the species vulnerability considerations, we recommend using the global aggregates in LCA studies

5 Based on the Countryside SAR.

6 The land use classes here are not using the same nomenclature as in Koellner et al. (2013b) but are comparable to 1.2.1 forest, used, extensive; 1.2.2 forest, used, intensive; 4.2 pasture/meadow; 5.1 agriculture, arable; 5.2 agriculture, permanent crops; 7.1 artificial areas, urban. It should also be mentioned that there are important land use classes important for biodiversity loss not covered by Koellner et al. (2013b): Tourism & Recreation areas; oil & gas extraction; mining; quarrying; renewable energy generation (i.e., wind turbines); utility & service lines; hunting & collection of terrestrial animals; gathering terrestrial plants (non-timber forest products); military exercise areas (Conservation Measures Partnership, 2015).

(by including a richer dataset in the result), to reflect the species vulnerability and to allow comparison with other life cycle impact assessment results.

This recommendation should be taken in consideration with the goal and scope of the LCA study and the practitioner should understand that the global CFs emphasize the impacts on endemic species. The disaggregated CFs per taxon can help the practitioner understand the results and provide insights into deeper assessments that might be done using tools outside of LCA, as reflected in section 6.8.

6.6.2 Evaluation and Verification of Characterization Factors

The appropriateness of the characterization factors has been tested in a limited number of case studies by the author (Chaudhary et al. 2016).

The availability of global and country-based averages allows considering and characterizing all land uses in a given product system of an LCA. However the accuracy and relevance of these highly aggregated values still needs to be verified.

6.6.3 Uncertainty

Uncertainty measures are provided on all aggregation levels and for all land use types with a 95% confidence interval for all CFs and all CFs are given with an average value, as well as a lower an upper value for the confidence interval. The uncertainties are modelled using Monte Carlo. Uncertainty is mainly driven by the affinity of the local studies, which means that the possibilities to further reduce uncertainties are limited. Such uncertainty values somewhat limit the ease of interpretation due to the significant overlaps expected to be observed between the potential species loss of alternative systems.

The full set of original characterization factors, including additional supplemental information is available on the ACS Publications website at DOI: 10.1021/acs.est.5b02507. Following the recommendations from this group, updated characterization factors including vascular plants were provided and are available in http://www.lifecycleinitiative.org/applying-lca/lcia-cf.

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Table 6.1: World average CFs calculated using Countryside SAR model and average approach per taxa aggregated

(Units – Global PDF/m² for occupation and Global PDF×year/m² for transformation). See http://www.lifecycleinitiative.org/applying-lca/lcia-cf for ecoregion and country CFs and disaggregated per taxa.

Land use type		Occupation avg regional	Transformation avg regional	Occupation avg global	Transformation avg global
Annual crops	Median	1,98E-14	2,88E-12	2,10E-15	2,50E-13
	lower 95%	-2,68E-15	-4,66E-13	-2,00E-16	-3,00E-14
	upper 95%	4,79E-14	7,78E-12	4,70E-15	6,60E-13
Permanent crops	Median	1,56E-14	2,31E-12	1,50E-15	1,80E-13
	lower 95%	-8,18E-15	-1,30E-12	-6,90E-16	-8,80E-14
	upper 95%	5,22E-14	8,47E-12	4,90E-15	6,70E-13
Pasture	Median	1,24E-14	1,88E-12	1,30E-15	1,50E-13
	lower 95%	-9,07E-15	-1,60E-12	-4,90E-16	-7,70E-14
	upper 95%	4,84E-14	8,39E-12	4,20E-15	5,90E-13
Urban	Median	2,91E-14	4,43E-12	2,40E-15	2,90E-13
	lower 95%	4,11E-16	6,46E-14	2,70E-17	2,80E-15
	upper 95%	5,42E-14	9,04E-12	4,90E-15	6,80E-13
Extensive forestry	Median	3,93E-15	6,08E-13	3,70E-16	4,20E-14
	lower 95%	-5,79E-15	-9,41E-13	-6,30E-16	-8,90E-14
	upper 95%	2,80E-14	4,50E-12	2,80E-15	3,90E-13
Intensive forestry	Median	1,05E-14	1,48E-12	1,10E-15	1,10E-13
	lower 95%	-9,78E-15	-1,60E-12	-7,10E-16	-1,00E-13
	upper 95%	4,61E-14	7,35E-12	4,10E-15	5,50E-13

6.7. Rice case study application

The purpose of the case study is to illustrate the practical implications of using the newly proposed CFs in a realistic situation, although the results of the case study should not be considered as a representation of specific production systems, rather illustrative cases that highlight pros and cons of the proposed CFs.

Table 6.2 shows the inventory data for land occupation (m^2year) of the land use classes differentiated by Chaudhary et al. (2015).

The characterization factors are based on ecoregion of the location where activity takes place. According to Frischknecht et al. (2016) it is assumed that the rice is produced in ecoregions IM0118, IM0120 and NA0409. For the purpose of comparison, different alternatives for background processes are considered as well as consequences of shifting foreground processes to potential nearby ecoregions.

Figure 6.3 shows the results using CFs for aggregated taxa, occupational average global CFs. Three different alternatives are shown to show the sensitivity of the assumptions on where activities takes place. In alternative 1 it is assumed that the rice is grown within the identified ecoregion, while for all other land use, including forestry for firewood, national averages are used. For the USA-Switzerland case, rice production is located to USA and its consumption in Switzerland. In alternative 2, it is assumed that all activities takes place within the identified ecoregion, while in alternative 3 world averages are used, except for rice growing that is assumed to take place in the identified ecoregion, and fuelwood for cooking, where average Indian values are used. For each scenario an average score is given, divided into land use classes, together with the total uncertainty using upper and lower values within the 95% confidence interval for all land use classes. All values are given in global PDF (see Chaudhary et al. 2015; http://www.lc-impact.eu/).

Figure 6.3 shows the importance of the included processes and their location for the final results. As the Figure shows, all included scenarios could potentially give negative values. Negative values are obtained as a result of potentially increased species richness compared with the reference situation, i.e., a higher species richness in the identified land use classes than in the selected reference situation (see Chaudhary et al. 2015). As the Figure shows, all cases have overlapping uncertainty ranges and no significant difference between the cases is thus found. However, it is clear that the results are driven by agricultural land use, and to a lesser extent forest when fuelwood is used.

If it is assumed that the land use is causing land use expansion, occupational marginal global CFs should be used instead. For the included cases this would not change the overall conclusion, which is the same irrespective of assumptions taken above; the biggest impact would be potentially caused by the foreground system during rice production (as described by the assumed production conditions); as well as to a lesser extent forest use for fuelwood.

Figure 6.4 below shows the scores when only the regional CFs are applied. The same assumptions as in the previous Figure are taken - it is assumed that the rice is grown within the identified ecoregion, while for all other land use, including forestry for firewood, national averages are used. As it can be seen, the ranking using average values changes

Table 6.2: Cradle-to-gate land occupation in m^2year per kg cooked rice for the different cases and land use classes given in Chaudhary et al. (2015).

	Rural India	Urban China	USA-Switzerland
Annual crops (foreground)	2.688	1.459	1.401
Annual crops (background)	0.003	0.003	0.003
Permanent crops	7.02E-05	7.14E-05	7.02E-05
Forest intensive	0.558	0.109	0.076
Forest extensive	2.87E-05	6.62E-05	3.34E-05
Urban area	0.010	0.010	0.097
Water bodies*	0.001	0.004	0.002
Total	3.261	1.584	1.579

* No CFs given for water bodies in Chaudhary et al. (2015) so these are not included in the further assessments.

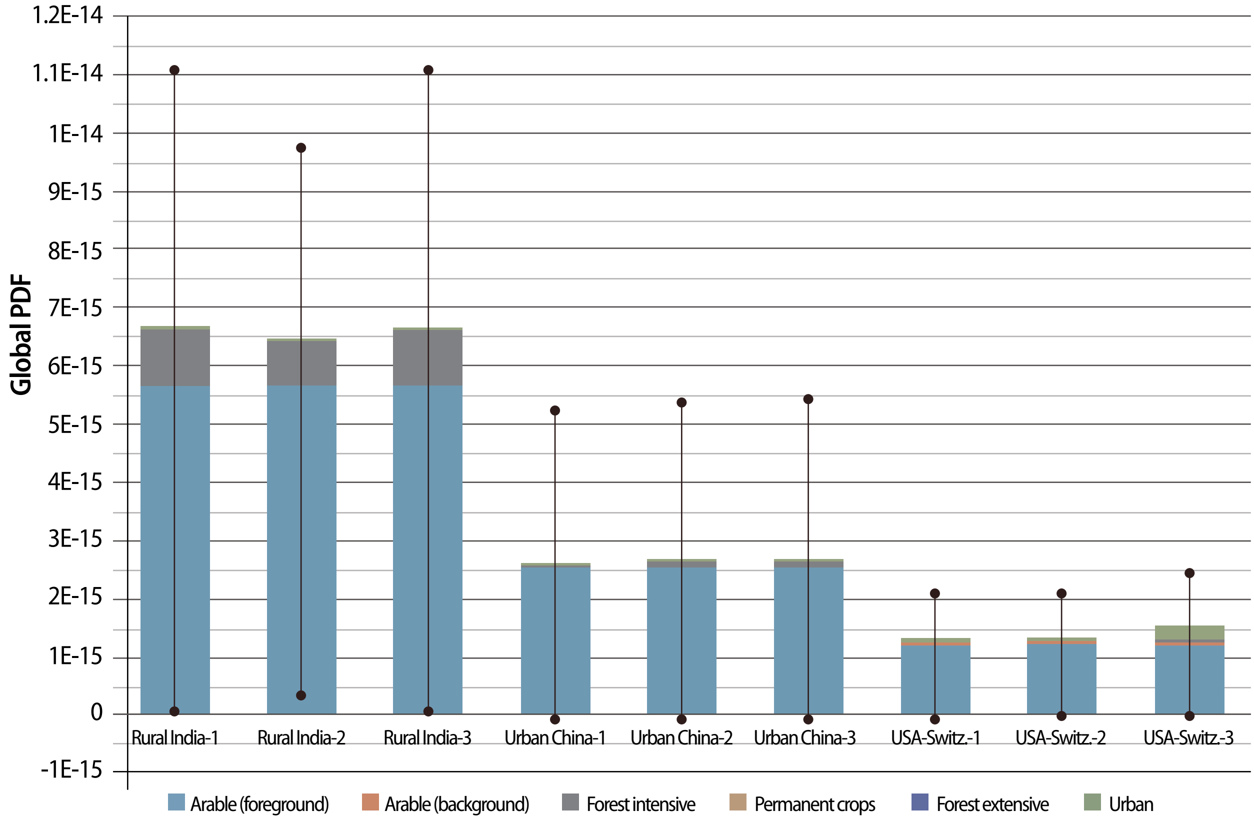

Figure 6.3: Global potential species loss (PSLglo) expressed as global PDF using CFs for aggregated taxa, occupational average global CFs in the illustrative case studies.

(the USA-Switzerland scenario has second largest potential impact), but all cases still have overlapping uncertainty ranges.

A challenge for all geographic-based CFs is that geographically close areas can have significantly different values, and thus uncertainty on the actual location drives overall uncertainty in the results. These differences can be caused by real differences in nature but may also be caused by the model itself (see e.g., Coelho and Michelsen 2014). To test the sensitivity of location, it was also tested what the scores would be if the USA-Switzerland case was located either to the nearby ecoregions NA0412 or NA0523. While NA0409 have the score 1.33E-15 (-3.25E-17, 2.10E-15), NA0412 scores 1.60E-15 (-3.70E-16, 3.73E-15) and NA0523 scores 1.03E-15 (3.00E-16, 2.51E-15). Again, all alternatives have overlapping uncertainty ranges and based on the given CFs.

Finally, Figure 6.5 shows the importance of different taxa in the results. In principle the LCA practitioner would not be expected to show this level of disaggregation in the results, but it could be made available. The advantage of showing what groups drive the potential impacts is that the user can easily

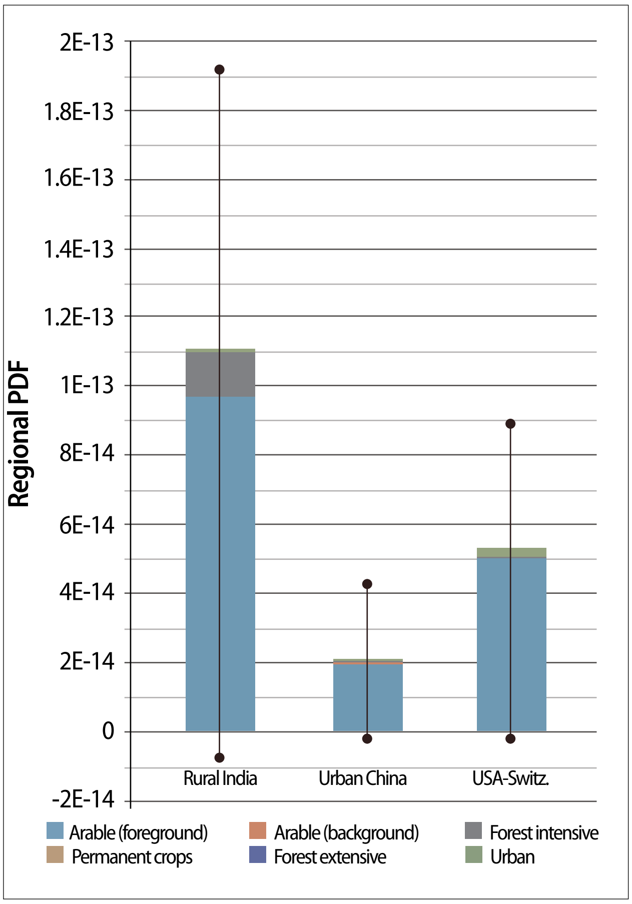

Figure 6.4: Regional potential species loss (PSLreg) expressed as regional PDF using CFs for aggregated taxa, occupational average regional CFs in the illustrative case studies.

identify whether the specific location or process showing as a hotspot is implementing specific measures to reduce such impacts, and/or whether the result would be meaningless with the specific knowledge of the place. Such information could then be utilized in the interpretation of the results. It is also important to highlight again that the model assumes that non-represented taxa would behave similarly to the ones that are included (mammals, birds, amphibians, reptiles), however, Figure 6.5 shows that different taxa behave differently in the eco-regions considered.

As recommended in section 6.8 below, the following four steps could be used as guidance to interpret the results:

1. **Specify the ecoregion where the process occurs to increase accuracy in your results and review the regional characterization factors for further insights into the main drivers of the hotspot.**

   The "hotspots" identified for each scenario include: rice production for all three scenarios and fuelwood production for the rural India scenario. The case study has already identified the specific eco-region in which the rice production occurs in each of the three scenarios, and a sensitivity analysis was conducted comparing the results of US production with two nearby eco-regions. The analysis reflected slightly higher impact potential for the two nearby eco-regions, but uncertainty ranges overlap significantly.

   Use characterization factors for eco-regions by taxa to look deeper into the results and identify which taxa for which land use are primarily at risk. In the included cases birds are most impacted by the rice production in the rural India case and the USA-Switzerland case, while amphibians are most impacted in the urban China case.

2. **Determine the local land use type and management characteristics or regime.**

   As the main agricultural processes (rice production in the case study) are foreground processes, it is likely that the practitioner or environmental manager would have access to information about the specific physical location and management activities of the production unit. The above insights on taxa should be compared with the

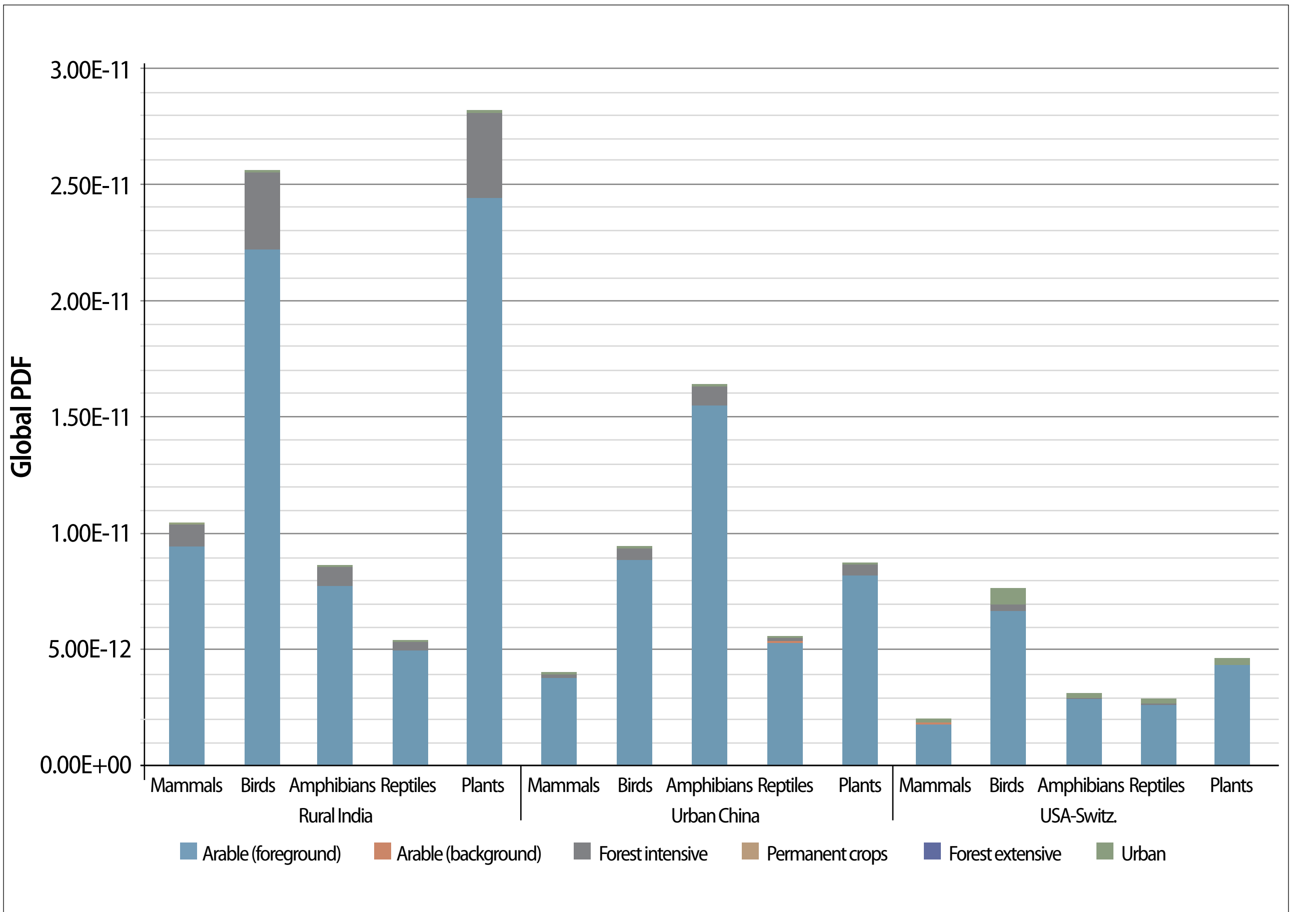

Figure 6.5: The importance of different taxa in global potential species loss (PSLglo) in the illustrative case studies (values for plants are divided by 100 to make them fit into the same figure).

local knowledge on biodiversity conditions on and surrounding the production area, including identification of critical habitat features for maintained biodiversity (e.g., high conservation value areas, care-demanding patches, etc.). Additionally, the practitioner is recommended to investigate the current management practices on the site, and whether any precautions to protect biodiversity have already been administered, and take those into consideration.

3. **Use more geographically specific or sector-specific biodiversity assessment methods, possibly including those that identify the conditions for maintained biodiversity (Michelsen 2008, Lindqvist et al. 2016); identify the criteria for responsible sourcing from that region or identify the criteria for responsible sourcing within a certain sector (e.g., LEAP guidelines, LEAP 2015).**

   Research into the criteria for sustainable sourcing from this region would reflect the existence of generic agricultural production certifications like the Sustainable Agriculture Network7. It would also reflect the work of a sector specific initiative, the Sustainable Rice Platform8, and its standard and performance indicators for sustainable rice production including a criterion on "protecting the natural environment from disruptive effects." If the practitioner can ascertain that the management recommendations are already implemented in the study areas, then it is suggested that the interpretation should suggest that the impact from the identified potential hotspots are likely to be significantly lower than indicated by given CFs provided by the recommended method.

4. **Take appropriate environmental management actions based on additional information.**

   In the case presented here, if the practitioner or environmental manager wanted to mitigate the risk of their production systems causing adverse impacts, they might inquire with the Sustainable Agriculture Network or the Sustainable Rice Platform about ensuring responsible sourcing.

7 www.san.ag, a third-party audited certification that includes four principles focused on the maintenance of wildlife and their habitat including specific performance criteria to measure success.

8 www.sustainablerice.org

6.8. Recommendations and outlook

6.8.1 Main recommendations

- As an interim recommendation, the global average characterization factors (CFs) based on the method developed by Chaudhary et al. (2015) are deemed suitable to assess impacts on biodiversity due to land use and land use change as hotspot analysis in LCA only. Please see further guidance below on moving from interim recommendation to full recommendation. These characterization factors are available for download from http://www.lifecycleinitiative.org/applying-lca/lcia-cf.
- We strongly recommend to use ecoregional CFs for foreground systems rather than country averages.
- The interim recommendation is to use the regional CFs as suitable to provide additional insights to the practitioner/environmental manager in further investigating identified potential hotspots.
- We strongly recommend that these CFs are not used for comparative assertions and product labelling. When used internally for product comparisons these CFs should not be used in isolation without further assessment of the specific biodiversity risks and potential management options, as suggested at the end of this section (Guidance for interpretation of results for LCA practitioners and environmental managers).
- We recommend that the indicator be given a name that explicitly states what it is measuring to avoid misinterpretation. Suggested name: Potential Species Loss from Land Use (Regional and Global - PSLreg and PSLglo)

Our reasoning for these recommendations includes (see Figure 6.6):

- This method allows global coverage of six major land use types, thus enabling the consideration of biodiversity impacts across most products' life cycles.
- The method takes into consideration many of the important aspects identified by stakeholders over the past two years of work by the task force, including: it builds on species richness; incorporates the local effect of different land uses on biodiversity; links land use to species loss through the Countryside-SAR model; includes

the relative scarcity of affected ecosystems; and includes the threat level of species (from IUCN lists, aggregating species vulnerability of specific habitats at the global level).

- The model is based on empirical observations and thus is not prone to judgment bias of the relative magnitude of change related to differentiated management practices on biodiversity.
- Based on the evaluation of indicators (Curran et al. 2016), the authors conclude that this indicator is the one likely to achieve better stakeholder acceptance at this point, both by LCA practitioners and ecologists.
- On the other hand, the recommendation is done ad interim because the method is very young and has not yet been tested in a wide range of product systems, regions, or application areas.
- There are limitations in land use types, management intensities, significant uncertainty, and other factors discussed below. Once this and the above consideration are solved the recommendation will stop being interim.

Conditions required to move from an interim recommendation to a full recommendation for hotspot analysis

Due to the limitations on maturity of the method and land use types and intensity coverage, the recommendation is considered ad interim until sufficient case studies are undertaken to test the robustness and ability of the model to identify potential biodiversity impacts. We recommend the following to be explored in the case studies:

1. Test the different major biodiversity threats from land use including: cropping, grazing, plantation forestry, and infrastructure;
2. Test its use on background data sets;
3. Test the sensitivities between land occupation and land transformation;

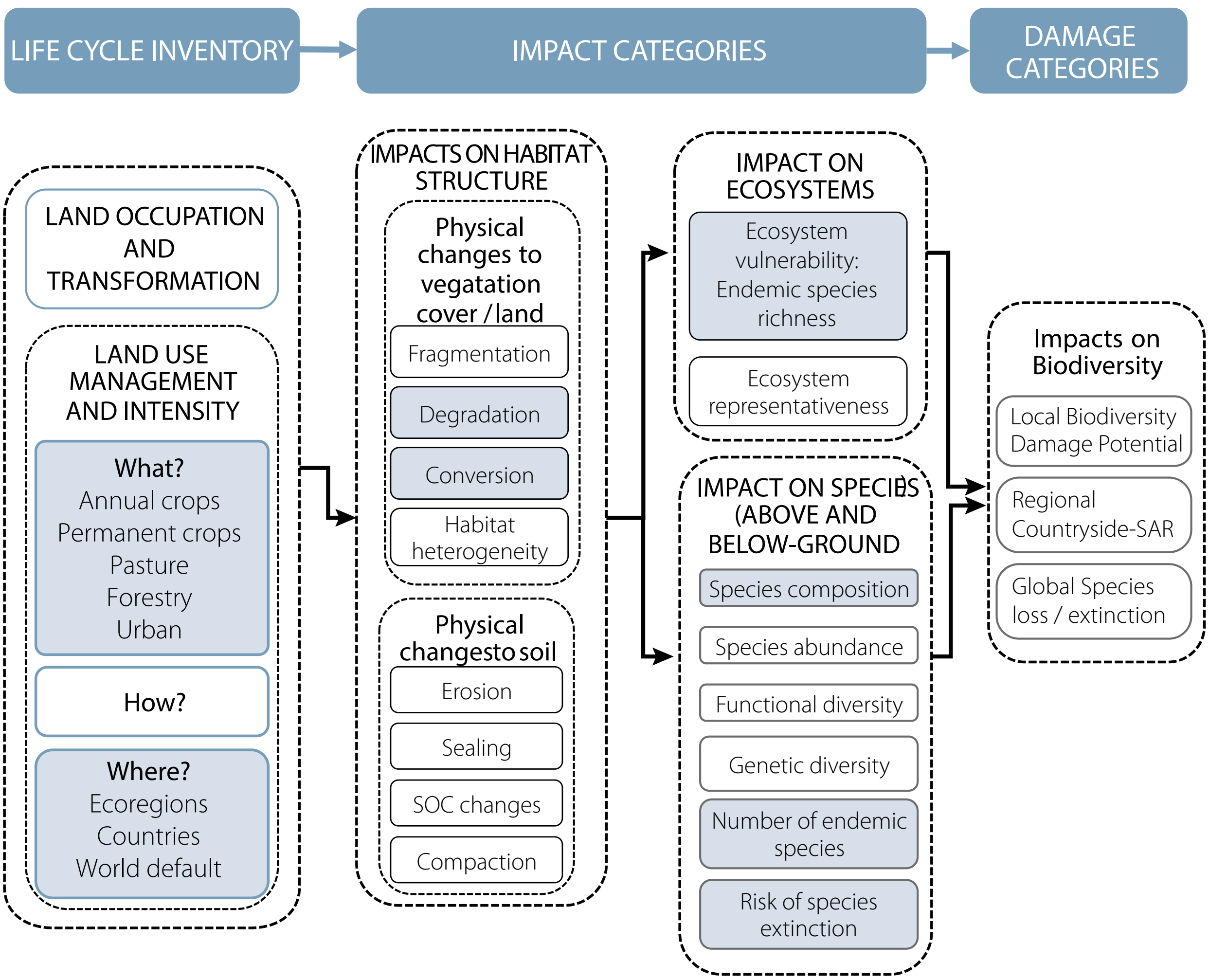

Figure 6.6: Aspects of the impact pathway covered by the method selected.

4. Compare against the global rate of extinction and/or the observed species loss within the studied systems;
5. Test the same process in multiple and diverse ecoregions (e.g., different biomes, different species conditions - umbrella species)

Suggested Areas of Improvement to Increase the Indicative Value of the Characterization Factors and Model Development

The following set of recommendations relates to improvements that we believe will strengthen the model:

- **Expand Land Use Classes**: Build a wider array of land use classes (including intensities) into the model based on the Koellner et al. (2013b) land classes and prioritize those land use classes that are the most impactful to biodiversity loss (e.g., agriculture, infrastructure development, etc).
- **Include Different Management Regimes**: The inclusion of management practices with scientific evidence proving their efficacy in protecting biodiversity to differentiate them from untested, unspecific, or average management practices.
- **Include Vascular Plants in Global CFs**: Include vascular plants into vulnerability weighting for the global CFs. This recommendation from the workshop was quickly taken up by the authors of the model during the production of this publication, and the recommended factors in this chapter (and available at http://www.lifecycleinitiative.org/applying-lca/lcia-cf) already include vascular plants in the vulnerability weighting.
- **Develop Best Practice Guidance**: Develop best practice information for use of the impact assessment including: procedures, manuals, and guidance (see additional recommendations under the stewardship section below).

6.8.2 Linking to Inventory Databases

In principle, LCA databases are already starting to consider the land use classification system suggested by Koellner et al. (2013b), which provides a significant level of intensity differentiation not yet catered for in the recommended model (Chaudhary et al. 2015). However it is recognized that the recommended model is lacking a number of land use classes which are important to biodiversity and may be included in future models.

The spatial dimensions of the CFs recommended will require some adaptation in life cycle inventory tools (LCA software) to use spatial information in the selection of the appropriate characterization factor at the impact assessment stage. It is also envisaged that other land use or land management attributes may be described at the process level or at the elementary flow level, which could be taken into account when calculating or selecting the characterization factor. The propagation of process and flow attributes and properties may be one important enabling factor to differentiate land use practices in impact assessment models in the future.

6.8.3 Linking to Life Cycle Impact Assessment methods

Given that many ecosystem quality indicators are currently being re-examined and developed for the first time by the LCA community, the following is recommended:

- While assumed to be relatively minor, assess any potential double counting between the impacts on biodiversity from land use and ecotoxicity indicators. This could be explored in a case study of an intensive agricultural system.
- Strive for complementarity between this model and the developments occurring in LCIA of ecosystem services, ecosystem functions, soil impact assessment methods, impacts on ecosystem quality from water use, and any other indicators that would be used alongside the recommended potential biodiversity loss indicator described in this chapter towards an ecosystem quality damage category (Mace et al. 2014).

6.8.4 Model Stewardship

In terms of outlook, the workshop participants proposed investigating the possibilities to provide stewardship for the model both regarding its further development and its current use. This could include support from the UNEP/SETAC Life Cycle Initiative. Activities could include:

- Provide ongoing steering for refining the consensus model. Some of the elements identified as important during the workshop include: exploring the comparison of systems with different management intensities and links with certification schemes; test effects of different reference states in the overall results; explore the inclusion of fragmentation effects in linear infrastructure, roads, and access; develop a tool or calculator (probably a spreadsheet with embedded data for reference studies, instructions to upload additional studies, etc.) to support LCA practitioners in the development of specific CFs for their foreground system processes, where this is recommended.

- Provide ongoing guidance, education, and training around use of the model, including its limitations (e.g., product labeling);
- Provide guidance to other complementary tools to manage identified biodiversity hotspots both within LCA (eg. Michelsen 2008, Coelho and Michelsen 2014) and external to LCA (e.g., biodiversity risk assessments, certification schemes).

Guidance for interpretation of results for LCA practitioners and environmental managers

Because the recommendation includes the restriction of the use of the method to hotspot identification only, additional guidance for practitioners and/or environmental managers to follow up on hotspot investigation is provided below. This type of guidance is similar to that provided in the interpretation of the results of the Social Hotspot Database (Benoit and Norris 2015).

If a potential hotspot is identified in the foreground system:

1. Specify the ecoregion where the process occurs to increase accuracy in your results and review the regional characterization factors for further insights into the main drivers of the hotspot.
2. Determine the local land use type and management characteristics or regime.
3. Use more geographically specific or sector-specific biodiversity assessment methods, possibly including those that identify the conditions for maintained biodiversity (Michelsen 2008, Lindqvist et al. 2016); identify the criteria for responsible sourcing from that region (e.g., credible sustainability certification schemes[9]); or identify the criteria for responsible sourcing within a certain sector (e.g., LEAP guidelines for the livestock sector).
4. Take appropriate environmental management actions based on additional information, such as the Conservation Measures Partnership[10].

If the potential hotspot is detected in the background system, using expert judgment, try to increase the accuracy of the results (country-specific CFs) to understand the relevance. If relevant, start at 3 above and follow the same steps.

6.9. Acknowledgements

We wish to thank the extensive work conducted by the members of the task force in the evaluation of the models, organization of expert workshops, and case study evaluation, as well as their contribution to discussions: Abhishek Chaudhary (ETH, Switzerland), Beatriz Vidal-Legaz (EC-JRC, Italy), Danielle Maia de Souza (SLU Uppsala, Sweden), Félix Teillard (FAO – LEAP), Greg Thoma, Jasmina Burek, William Puttman (University of Arkansas, USA), Jan Paul Lindner (IBP, Germany), Maria Cléa Brito de Figueirêdo (EMBRAPA, Brazil), Michael Curran (ETH Zurich, Switzerland), Serenella Sala (EC DG JRC), Pieter Elshout (Radboud University, Nijmegen The Netherlands), Ricardo F. M. Teixeira (Terraprima, Portugal), Simone Fazio (European Commission JRC/DG Environment), Carla Coelho (French National Institute for Agricultural Research, Rennes France), Béatrice Bellini (U Versailles), Eugenie Regan, Sharon Brooks, Matt Walpole (UNEP-WCMC). In addition, a longer list of experts participated in the workshops during the work of the task force, and their contribution is kindly appreciated. Finally, the discussions with other participants during the Pellston workshopR, in particular with Cássia Ugaya, Cléa Figueirêdo, Yuki Kabe, Francesca Verones, and Stefanie Hellweg were extremely helpful to improve the relevance and acceptability of the recommendations.

9 Industry, some NGOs and other stakeholders often recommend for this purpose the certification schemes established by the Sustainable Rice Platform, Roundtable of Sustainable Palm Oil, Rainforest Alliance's Sustainable Agriculture Network, etc.

10 Conservation Measures Partnership "IUCN-CMP Threats Classification v 2.0" http://www.conservationmeasures.org/beta-versions-of-the-iucn-cmp-threats-and-actions-classifications-available/

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7. Integration and synthesis

Rolf Frischknecht, Olivier Jolliet, Llorenç Milà i Canals, Stephan Pfister, Abdelhadi Sahnoune, Cassia Ugaya, Bruce Vigon

7.1 The SETAC Pellston Workshop® process

This guidance document is a result of intensive efforts by an international group of experts to identify consensus on selected environmental impact category indicators, on the overall life cycle impact assessment framework, and on crosscutting issues. A careful evaluation of existing environmental impact category indicators representing climate change impacts, human health impacts caused by particulate matter, water scarcity, and human health impacts due to water use, as well as biodiversity impacts related to land use was brought to a focused analysis process. Findings and recommendations on these indicators, on the overall framework, and on crosscutting issues are presented in the previous chapters. These recommendations show a variable level of maturity and degree of reliance and confidence, which need to be taken into account when applying the recommended indicators.

The topics addressed are not stand-alone, but have the potential of being integrated into the bigger picture of life cycle impact assessment. This chapter provides such an integration and synthesis, as well as key messages of the topics covered. One element of this integration encompasses the overall framework and crosscutting issues to which all recommended environmental impact category indicators refer. Developing further environmental impact category indicators systematically in line with the overall framework and adhering to the recommendations related to crosscutting issues is highly important and strongly recommended by the guidance principles. This will foster the application and the acceptance of life cycle-based environmental indicators and facilitate the development of comprehensive and consistent life cycle impact assessment (LCIA) methods.

7.2 Overall framework and crosscutting issues

Currently there are a number of crosscutting issues that need harmonization, either across all impact categories and damage categories (previously named areas of protection, Jolliet et al. 2004, #2608) or within a specific damage category, such as standardization of spatial resolution or of its description, harmonized endpoint indicators, and normalization procedures.

The main novelties emerging from the workshop are:

- an updated LCIA framework distinguishing intrinsic, instrumental, and cultural values to encompass six damage categories (human health, ecosystem quality, cultural heritage, natural heritage, socio-economic assets, as well as natural resources and ecosystem services)
- guidance to improve consistency of the approach across reference states, spatial differentiation, and time frames

A number of recommendations are listed in Chapter 2 for method developers and practitioners. For the former, the following is highlighted:

- We strongly recommend documentation is made more transparent, especially regarding the impact pathway, units, reference states, uncertainties, spatial scale, modeling and data choices, and the rationale for those.
- We strongly recommend that the spatial scale of regionalized models reflects the nature of impact, that CFs are reported at the original and aggregated scale, both with information on uncertainty and variability.
- We recommend that, if possible, quantitative uncertainty is reported for CFs; otherwise, qualitative descriptions of uncertainty should be provided
- We recommend that CFs for two different time horizons (till 100 years and long-term), are provided whenever relevant, and in a way that makes them additive
- We recommend that consistent global normalization references are provided
- We recommend the characterization of ecosystems and/or species in a way that takes resilience, rarity, and recoverability into account
- We advise that marginal and average characterization factors are provided, which are, respectively, more suitable for studies of small and large systems
- We advise that the reference state is consistent across impact categories

Additionally, we recommend that practitioners use global normalization values and report transparently the selected normalization and (if applicable) weighting approaches, and the rationale behind these choices.

Not all the discussed points, however, were suitable for final recommendations. This is mainly because the knowledge on these topics is not yet sufficiently developed and/or the understanding on the approaches proposed is yet limited. Thus, future research is required, in particular on the following topics:

- Investigating and agreeing upon a framework for uncertainty assessment of impact assessment methods and improving the quantitative uncertainty assessment
- Including and developing methods to assess instrumental damages to socio-economic assets, ecosystem services, and resources
- Strengthening current biodiversity impact approaches through inclusion of vulnerability
- Developing approaches for weighting of CFs at different ecosystem scales or different taxa
- Investigating options to operationalize methods dealing with ecosystem services
- Coordinating with life cycle inventory and LCA software developers to ensure inclusion of uncertainty assessments
- Testing methods that provide both marginal and average effect factors with case study applications
- Developing consistent sets of global normalization values and references

7.3 Greenhouse gas emissions and climate change impacts

Global warming potential (GWP) with a time horizon (TH) of 100 years is the most widely quoted metric in all LCIA methods when quantifying climate change impacts from emissions of greenhouse gases (GHGs). With the recent advances in climate science, it has become evident that while still relevant, GWP100 is only one of the possible metrics. Other metrics can provide complementary information to decision makers about the climate change impacts of a product or system. Some GHGs, also referred to as well-mixed GHGs (WMGHGs), have lifetimes that last years to millennia. They contribute to the rate of change and to the long term increase in global temperature. Near term climate forcers (NTCFs), like ozone precursors and aerosols, have lifetimes from a few days to a few months. At present, there is no single indicator that can adequately inform about the climate impact dynamics from such a variety of forcing agents and lifetimes. The task force on global warming reviewed the recently proposed metrics in the IPCC fifth assessment report (IPCC AR5) and came to the conclusion that it makes sense to use several complementary metrics that serve different purposes to understand how LCA results are sensitive to different modeling choices. Workshop participants arrived at the recommendation to use two impact categories, one for shorter-term impacts (based on GWP100), targeting contributions to the rate of warming, and the second for long term temperature changes (based on global temperature change potentials, GTP100).

The proposed units for GWP100 and GTP100 are kg CO_2e (short) and kg CO_2e (long), respectively. Their values are not to be combined to generate a total impact, as they represent different impacts. When calculating these metrics, climate-carbon cycle feedbacks for both non-CO_2 GHGs and CO_2 have to be considered for more consistency, as recommended in IPCC AR5. Contributions from NTCFs have been usually excluded in LCA, despite their potential significant impacts on the climate system. The latest IPCC assessment report summarized emission metrics for NTCFs as well, which are affected by larger uncertainty ranges than metrics for WMGHGs. For NTCFs, it is thus recommended to perform sensitivity analyses using the range of values summarized in Chapter 3, including GWP20 as alternative characterization factors for shorter term impacts.

7.4 Health impacts of fine particulate matter

To date, health impacts of particulate matter (PM) and specifically the respirable fraction of PM less than 2.5 microns in mass median diameter, termed $PM_{2.5}$, have not been consistently incorporated in LCIA modeling. One of the major goals of the PM task force was to rectify this situation using the latest science and fate and effects modeling, and to ensure the results of the LCIA modeling was consistent with the epidemiologic literature for relevant indoor and outdoor environments. The primary reference data source driving this effort is the Global Burden of Disease last updated and published in 2015.

The task force effort resulted in a number of innovations that brought an LCIA approach to address health impacts from exposure to $PM_{2.5}$. In a kick-off experts workshop several issues were identified and evaluated by the task force members and then organized by priority, relevance, and feasibility. Among the task force innovations are specific recommendations to address a variable range of source-to-exposure archetypes and the ability to treat secondary $PM_{2.5}$ (formed in the atmosphere from gaseous precursors), as well as primary $PM_{2.5}$.

Although the most fundamental form of the $PM_{2.5}$ model conforms exactly to the decades old standard of IMPACT = EMISSION X CF, the elaboration of this model within the archetypes and within an LCA framework required numerous innovations in both the source-to-exposure component (population intake per kg emitted) and in the exposure-to-impact endpoint assessment, with impact expressed in cumulative disability-adjusted life years (DALYs) per kg intake.

In developing a framework for addressing PM2.5 in LCIA, the task force made a number of overarching and specific recommendations. Many of these recommendations deal with actions that increase both the reliability of and confidence in modeling exposure and applying exposure-response functions (ERFs) in the context of available data. The task force found that modeling results closely matched monitoring data in several situations, thus lending confidence to the actions proposed. The task force's main recommendations address both the process for linking emissions to exposure and the process for linking exposure to disease and mortality. Summarized and prioritized below are overarching recommendations.

Strong Recommendations:

- Use the intake fraction to capture source-receptor relationships for both primary and secondary $PM_{2.5}$ for both outdoor and indoor emissions.
- Organize impacts and exposures organized according to whether emissions originate outdoors or indoors, in urban or rural regions, and as ground-level versus stack emissions. Where possible use city-specific intake fractions to capture large intra-urban variability.
- Make use of available and well-vetted exposure-response models for assessing both total mortality and disease-specific DALYs associated with $PM_{2.5}$ exposures both indoors and outdoors.
- Include background exposure to $PM_{2.5}$, as well as background disease incidence (and/or mortality) in the calculation of impacts for any selected population to ensure proper application of these models to LCIA.

Recommendations:

- Make use of interim recommended generic factors for very high, high, and low stack emissions based on the use of ground level emissions and correction factors from current literature until better models become available.
- Make use of current literature values for secondary $PM_{2.5}$ formation indoors.
- Include qualitative and (when possible) quantitative characterization of variability and uncertainty.

Interim Recommendations:

- Make use of global exposure distributions to characterize the impacts of emissions when emission locations are not specified and in the absence of more detailed data or information.
- Use high-background indoor $PM_{2.5}$ values associated with solid fuel cooking in regions where these data are available.
- Focus on primary $PM_{2.5}$ impacts in urban areas when detailed models of secondary $PM_{2.5}$ formation are not available.

7.5 Water use related impacts: Water scarcity and human health effects

7.5.1 Water scarcity

According to the ISO water footprint standard, water scarcity is the "extent to which demand for water compares to the replenishment of water in an area, such as a drainage basin." While most existing water scarcity indicators were defined to be applicable either for human health or ecosystems impacts, we developed a generic water scarcity indicator. However, in addition to this scarcity aspect, the group designed an indicator that allows for absolute availability to be reflected as well, based on the outcome of a two-year consensus building activity by the water use in life cycle assessment (WULCA) working group. The CF aims to answer the question, "What is the potential to deprive another user (human or ecosystem) when consuming water in this area?" It is calculated on watershed level (~11'000 units) and on a monthly level with global coverage.

Based on the evaluation of different methods we recommend the use of the "AWARE" approach, which is based on the quantification of the relative Available WAter REmaining per area once the demand of humans and aquatic ecosystems has been met. In other words, the method quantifies a surface-time equivalent that would be required to replenish the water consumed without depriving other users. In areas where current demand already exceeds availability in a watershed and a specific month, a cut-off value is required. This value is set at 100 times the global average value on the upper hand and also limited to 0.1 of global average situation at the lower end, in order to limit the span. Due to the conceptual difference with previously existing scarcity indicators, we strongly recommend performing a sensitivity analysis with a conceptually different method to test the robustness of the results, keeping in mind that different results are sometimes to be expected.

In terms of choice of spatial and temporal scale, we strongly recommend applying CF at monthly and WS scale if possible. If for practical reasons (e.g., background data) this is not possible, we strongly recommend to use sector-specific aggregation of CF on country and/or annual level (differentiated for agricultural and non-agricultural use). Our least recommended approach is to apply generic CFs on country-annual level. Global CFs are provided but not recommended for use.

Additionally, it is important to provide non-marginal characterization factors that will be applied to bigger changes and footprint studies. To better assess crop production, which dominates global water consumption, we suggest that CFs aggregated on year and annual level could be calculated to represent crop-specific patterns based on growing seasons and watersheds. This would allow higher precision when assessing crops with crop-specific aggregation of CFs, when month and watershed is unknown.

Any aggregation shall include uncertainty information induced by the underlying variability.

7.5.2 Human health effects

Domestic and agricultural water scarcity has been recognized as a relevant pathway in which water consumption may lead to damage of human health. While water deprivation for domestic use may increase the risks of intake of low quality water or lack of water for hygienic purposes, water demand in agriculture (irrigation) and fisheries or aquaculture are necessary for human nutrition in many areas of the world. In this context, deficit of water in agriculture and fisheries or aquaculture may decrease food production, and consequently result in the increase of malnutrition damage due to the shortage of food supply.

Human health characterization factors specifying DALY lost from reduced food production have been modeled based on existing publications. In addition to these methods, the human health endpoint CF includes inequality adjusted adaptation capacity on country level to better reflect exposure of a population to food deficit. The trade model has been improved, including the consideration of stock of food in each country. Moreover, the "fate" factor based on scarcity has been aligned to consider a similar reasoning as the AWARE recommendation, i.e., including available water remaining for human uses.

The characterization factors for human health are recommended for use. High uncertainties in the modeling are highlighted and should be assessed in LCIA. The CFs are provided on watershed and monthly level and it is strongly recommended to apply them at this level of resolution. For practical applications, temporal and geographical resolution of inventory might be missing, therefore country and global average values are provided, including uncertainty induced by variability within countries and months. Global CFs are provided but not recommended for use. The characterization factors provided together with this publication are recommended for marginal applications only.

The effects of water use on human health quantified with the recommended indicator are based on a series of potentially valid but yet unproven assumptions, based on previous published literature. In future research, additional refinement of the modeling of the adaptation capacity (e.g., sub-regional maps of GDP (PPP) per capita) should be investigated to increase robustness of the malnutrition vulnerability (relating DALY to lack of food supply), as well as for improving the trade effect. The trade effect model should be enhanced in future research to better account for price elasticity and its effects on nutrition. Further investigation about the robustness of the use of calories deficit relation to protein-calories malnutrition is required and more specific data on regional health responses to malnutrition should be investigated.

Since no CF are ready for suggestion to be used, additional analyses are required for the assessment of the cause-effect relationship between domestic water scarcity and damage associated to lack of water for sanitation (i.e., water-related diseases). In particular, the question to what extent these effects are triggered by an additional water use in an area should be further investigated.

Finally, water quality aspects or source of water availabilities (e.g., ground or surface water) need to be assessed once global data of satisfying quality becomes available.

7.6 Land use related impacts on biodiversity

Building on the important methodological developments that have taken place in the last few years, this workshop provides a significant breakthrough in the recommendation of a model and indicator allowing the consistent consideration of potential species loss from land use in LCA. Enabling the routine and consistent consideration of land use impacts on biodiversity among the impact areas commonly considered in LCA is thus the main contribution of the consensus built among the experts in the workshop. Additionally, the value and robustness of the method suggested also merits highlighting. Indeed, the indicator recommended by the authors addresses a significant share of the aspects considered as important by stakeholders in the assessment of biodiversity impacts. Namely, the model builds on species richness; incorporates the local effect of different land uses on biodiversity; links land use to species loss; includes the relative scarcity of affected ecosystems; and includes the threat level of species.

On the other hand, the limitations of the model in addressing the inherent complexity of biodiversity have also been highlighted, in particular the limited number of taxa covered (vascular plants, mammals, birds, amphibians, reptiles); the exclusion of attributes of genetic or ecosystem diversity and of processes such as fragmentation; and the deficient capture of effects of main land management practices on biodiversity.

As an interim recommendation we propose the global average characterization factors (CFs) quantifying potential species loss (PSL) from land use and land use change and suitable for hotspot analysis in LCA. We strongly recommend against using these CFs for comparative assertions. When used internally in a company for product comparisons we recommend against using it in isolation without further assessment of the specific biodiversity risks and potential management options.

The CFs provided are applicable in hotspots analysis from LCA, thus guiding in the identification of regions and processes requiring special attention due to their potential impact on biodiversity. The users are guided on the interpretation when such hotspots are identified, and the follow-up assessments required. Even though the implementation of the CFs provided will require some mapping effort by the practitioners (and eventually by LCA database managers) of the land use flows used in the recommended method to those specified in the main life cycle inventory nomenclatures, the model is deemed applicable for practical use in current LCA software and practice.

Some immediate developments are required to upgrade the interim recommendation to full recommendation of CFs. These improvements comprise the refinement of land use classes considered including different management regimes, the inclusion of additional taxa, the development of best practice information for use, and interpretation of the impact assessment results, as well as testing of CFs in sufficient case studies to explore the robustness and ability of the model to identify potential biodiversity impacts.

7.7 Achievements, vision, and roadmap(s)

The work and discussions before and during the Pellston Workshop® resulted in relevant recommendations in the four topical areas climate change, particulate matter, water use impacts, and land use impacts, as well as with regard to the LCIA framework and cross-cutting issues. The characterization factors and impact category indicators recommended include latest findings of topical research and clearly go beyond current practice. The levels of recommendation show the variable maturity of the indicators (see Table 1). At the same time, care has been taken to ensure immediate applicability in current LCA environments.

Hence, this workshop format turned out to promote progress in science and at the same time foster the practicality and robustness of the recommended indicators.

Given the dynamics in this research area, the recommended characterization factors should not be seen as given and static, but rather evolutionary. Expected and welcome changes will further improve the robustness, topical coverage, and applicability of the environmental impact indicators recommended today.

The Pellston Workshop® successfully proved the willingness of co-operation in the field of LCIA research and development. The task forces should maintain and increase the momentum achieved through this effort. The Life Cycle Initiative should take care of the stewardship of the recommended indicators and characterization factors. The Life Cycle Initiative should help build a structure for a community of LCIA research teams and organizations to maintain the consensus indicators and characterization factors. This community may start with the task forces dealing with the topics discussed during this Pellston Workshop®. The community should take care of capacity building and establish recommendations on the proper use and interpretation of the environmental indicators they developed. The community may grow when launching consensus finding processes for additional environmental impact indicators such as acidification & eutrophication, human toxicity, and mineral resource depletion.

Spatial resolution is an issue common to three out of the four topical areas, i.e., particulate matter emissions, water use impacts, and land use impacts. All three groups agreed on providing characterization factors on the native scale (like watersheds or ecoregions), as well as on more aggregated levels such as countries, continents, and the globe (water use impacts and land use impacts), or archetypes such as indoor or outdoor and rural or urban (PM).

While the need for spatial differentiation is acknowledged in decision situations dealing with the foreground system, it is a challenge to underpin spatially explicit product LCA models with the LCI data and information required. Thus, it is an important task to derive smart and parsimonious approaches from the knowledge gained in LCA research projects in which a high geographic resolution is applied.

The United Nations Sustainable Development Goals (United Nations 2015) cover topics such as climate action (goal 13), clean water and sanitation (goal 6), life on land (goal 15), and good health and wellbeing (goal 3). It will be a promising and important challenge to explore the possibilities of using the environmental indicators recommended in this report in supporting actions to improve the environmental situation and to monitor progress relative to selected sustainable development goals. Similarly, we strongly recommend exploring options and opportunities on how to make use of the environmental indicators when quantifying environmental planetary boundaries.

7.8 References

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United Nations (2015) Resolution adopted by the General Assembly on 25 September 2015: Transforming our world: the 2030 Agenda for Sustainable Development. United Nations General Assembly, New York, USA.

Table 7.1: Characteristics of the environmental life cycle impact category indicators recommended, their domain of applicability and the level of recommendation

Impact category and subcategory	Cause-effect description	Indicator retained - Position in the cause effect chain Metric Unit	Factors of influence - Considered, spatial resolution Archetypes Time horizon	Domain of applicability	Level of recom-mendation
Climate change impacts					
Shorter-term climate change (rate of climate change, impacts related to the adaptation capacity of humans and ecosystems)	Cumulative Radiative forcing	Global warming potential (GWP) kg CO_2e (short)	Global 100 years	No restrictions	Strongly recom-mended
Long–term climate change (long-term temperature increase and related impacts on ecosystems and humans)	Instantaneous Temperature	Global temperature change potential (GTP) kg CO_2e (long)	Global 100 years	No restrictions	Strongly recom-mended
Particulate matter impacts					
Health effects caused by primary and secondary fine particulate matter	All-cause mortality	Number of deaths per kg emitted	Indoor/outdoor Urban/rural Ground level, low/high/ very high stack	Global, using archetypes as described left	Strongly recom-mended, interim
Water use impacts					
Scarcity	Surface-time equivalent required to generate one cubic meter of unused water	Surface time equivalents (STE) m^3 world eq./m^3i	Native scales: Geographic: Watersheds Temporal: Month Use: Agricultural/industrial Integration to regions, countries, continents and global	Global, marginal impacts generated by < 5 % of total water consumption in a given area	Recom-mended
Health effects	Impacts caused by malnutrition	Change in water availability to agricultural production due to water consumption	Native scales: Geographic: Watersheds Temporal: Year Integration to regions, countries, continents and global	Special attention recommended to the interpretation of food-producing systems	Recom-mended
Land use impacts on biodiversity					
Potential species loss	Effect of land occupation displacing entirely or reducing the species which would otherwise exist on that land	Indicator accounts for the relative abundance of species and their overall global threat level	5 taxa (birds, mammals, reptiles, amphibians and vascular plants) Geographic: 800+ ecoregions Reference state: Natural habitat	Hot spot analyses, Not to be used in comparative assertions disclosed to the public	Recom-mended, interim

Glossary

Aggregated spatial scale	A transformation of the native spatial scale to a fewer number of spatial units with larger areas, usually at a country or continental scale. Aggregated spatial scales are used in calculation methodologies that are not completely regionalized.
Background system	The background system consists of processes on which no or, at best, indirect influence may be exercised by the decision maker for which an LCA is carried out. Such processes are called "background processes" (Clift et al. 1998).
Biodiversity	Variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic systems and the ecological complexes of which they are part, including diversity within species, between species, and of ecosystems (Article 2 of the Convention on Biological Diversity, UN-1992).
Biome	The world's major communities, classified according to the predominant vegetation and characterized by adaptations of organisms to that particular environment. For instance, tropical rainforest, grassland, tundra (Campbell 1996).
Coarse PM	Mostly defined as the between 2.5 and 10 µm fraction of PM10 (Wilson and Suh 1997)
Conditions for maintained biodiversity (CMB)	These relate to key factors important for biodiversity, such as dead wood in a boreal forest (Michelsen 2008).
Countryside SAR	The countryside SAR classifies species into functional groups with particular affinities for different habitats in a given area (landscape) (Pereira et al. 2014), and predicts that species adapted to human-modified habitats also survive in the absence of natural habitat (Chaudhary et al. 2015).
CRF	Concentration-response function: The slope and/or shape of the relation between the frequency [rarely severity] of a selected health outcome in the target population vs. [usually centrally] monitored concentration of a selected air contaminant
Current state reference	Use of current regional average species richness as a reference for assessing species richness (Koellner and Sholz 2008).
DRF	Dose-response function: The slope and/or shape of the relation between the frequency [rarely severity] of a selected health outcome in the target population vs. absorbed dose of a selected air contaminant
Ecoregion	Large unit of land or water containing a geographically distinct assemblage of species, natural communities, and environmental conditions. (WWF, http://www.worldwildlife.org/biomes, accessed date 18/03/2016).
Ecosystem	A dynamic complex of plant, animal, and micro-organism communities and their non-living environment interacting as a functional unit (Article 2 of the CBD).

Ecosystem services	The benefits people obtain from ecosystems. These include provisioning services, such as food and water; regulating services, such as flood and disease control; cultural services, such as spiritual and recreational benefits; and supporting services, such as nutrient cycling that maintain the conditions for life on Earth (MEA 2005).
Endemic species	See Endemism
Endemism	Association of a biological taxon with a unique and well-defined geographic area. [The Encyclopedia of Earth, http://www.eoearth.org, accessed 18/03/2016]
ERF	Exposure/response function: The slope and/or shape of the relation between the frequency [rarely severity] of a selected health outcome in the target population vs. monitored or modelled exposure [contact concentration] to a selected air contaminant
External normalization	Normalization by references, which could be the impacts generated by a region or other types of entities (e.g. organization) independent of the object of the LCA in a given time period. In relevance to the report, approaches include: Global normalisation (assuming production same as consumption) Production-, territorial-based normalization (reference includes territorial activities in a region or country, including impacts associated with its exports but excluding those related to its imports)
Fine PM	Synonym for PM2.5 (fine particulate matter)
Foreground system	The foreground system consists of processes that are under the control of the decision-maker for which an LCA is carried out. They are called "foreground processes" (Clift et al. 1998).
GBD	Global burden of disease: The number of DALYs [disability adjusted life years] lost by the [global] population due to a given causal factor and/or disease (WHO World Health Organization 2008)
Habitat	The place or type of site where an organism or population naturally occurs (Article 2 of the CBD Convention on Biological Diversity, UN-1992).
Hotspot, biodiversity	A hotspot for biodiversity represents a geographical area where there is a coincidence of high biodiversity and high level of biodiversity threats (FAO 2016).
Hotspot, hotspot analysis, LCA	Within an LCA study a hotspot is a relevant environmental aspect and its position in the life cycle. A hotspot analysis covers the identification of relevant processes and potential impacts for further investigation within the LCA study.

Intake Fraction (iF)	The proportion of agent that is emitted/released into the environment, which is eventually inhaled, ingested or dermally absorbed by the target population. In the current paper, the proportion of emitted primary PM2.5 or precursor of secondary PM that is inhaled by the target population.
Intensity	Degree of labor operations related to crop production. An intensive agriculture system involves the cultivation of limited areas and relies on the maximum use of labor and expenditures (machinery, chemicals) to raise the crop yield per unit area (opposed to extensive).
Internal normalization	Normalization by references linked to the alternative(s) assessed in the study (alternatives are defined as any compared systems, whether they relate to different scenarios of a same product system or to different product systems). It is applied exclusively in comparative LCAs with the goal of helping guide a selection (choice problem). Examples are division by baseline, i.e. the reference is the characterized indicator results obtained for one alternative (= baseline)
Land use	Within LCA, land use is a data category revealing land transformation [m^2] and occupation [m^2a] (Milà i Canals et al. 2007). More generally, land use refers to the functional dimension (i.e., use) and corresponds to the description of areas in terms of their socio-economic purposes – how the area is used for urban activities, agriculture, forestry, etc. Another approach to land use is termed sequential, and it refers to a series of operations, particularly in agriculture, carried out by humans in order to obtain products or benefits through using land resources. Contrary to land cover, land use is difficult to "observe." For example, it is often difficult to decide if grasslands are used or not for agricultural purposes. By the definition of IPCC (2007a), land use refers to the total arrangements, activities, and inputs undertaken in a certain land cover type (a set of human actions). The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction, and conservation) (Mattila et al. 2011).
LPD	[Average] linear population density over a specified area, e.g., a city: total population (#) divided by the square root of the urban area (m2).
Matrix SAR	The matrix SAR incorporates the effects of habitat provided by human-modified land and account for taxon-specific responses to each component of a heterogeneous landscape (Chaudhary et al. 2015).
Native spatial scale	The spatial scale of the published LCIA method chosen by LCIA method developer as the best scale to represent the spatial variability of CF values.
PM2.5	Usually refers to particles with aerodynamic diameter smaller than 2.5 µm. The exact definition; however is the particle fraction which is captured by the US EPA standard reference method [or equivalent] for PM2.5 sampling, which includes some particles with an aerodynamic diameter larger than 2.5 µm and excludes some particles smaller than 2.5 µm.
PM2.5 of ambient [or outdoor] origin	The ambient [or outdoor] component of total personal exposure to PM includes exposure to the ambient PM concentration [as measured by the monitoring network] while outdoors and exposure while indoors to ambient PM that has infiltrated indoors (Wilson and Brauer 2006).

PM2.5 of non-ambient origin	The non-ambient component of total personal exposure to PM refers to exposure to PM generated by indoor sources and an individual's personal activity. As expected, the non-ambient exposure was not related to the ambient concentration (R2<10-6) (Wilson and Brauer 2006).
PM2.5 of indoor origin	Often used interchangeably with PM2.5 of non-ambient origin, but, to be exact, does not include the PM2.5 exposure originating from an individual's personal activity.
Primary PM2.5	PM2.5 that was originally emitted/released into the atmosphere in solid or liquid phase.
Reference state	Reference state is a baseline used as a starting point to which to quantitatively compare another situation. A reference state can be, for example, a (hypothetical) situation representing conditions in the absence of human intervention, an anticipated or desirable target situation or the current situation. A reference state refers to a time period and space.
Regionalized impact assessment	Characterization of elementary flows using characterization factors, which have different values depending on the location of the elementary flow.
Scarcity	A situation in which something (species) are not easy to find
Secondary PM2.5	PM2.5 which has been generated in the atmosphere from gas or vapour phase precursors via chemical and/or physical processes. In ambient air the secondary PM mostly consists of ammonium sulphate, ammonium nitrate and secondary organic aerosols (SOA, either condensed from organic carbonaceous vapours or generated via oxidation of terpenes and other reactive volatile organic compounds (VOC)). The same processes occur in indoor air, dominated by SOA formation.
Site-generic impact assessment	Characterization of elementary flows using a single characterization factor without any spatial variation.
Spatial scale	The "spatial extent of the operation of a particular phenomenon."(Jenerette and Wu, 2000)
Spatial unit	The geometrical definition and metadata of a spatial feature, such as a raster cell or polygon.
Umbrella Species	The concept of an umbrella species has been used by conservation practitioners to provide protection for other species using the same habitat as the umbrella species. As the term implies, a species casts an "umbrella" over the other species by being more or equally sensitive to habitat changes (The Encyclopedia of the Earth http://www.eoearth.org/view/article/156765/, data accessed 18/03/2016).
Uncertainty (spatial)	uncertainty of estimates at native scale
Variability (spatial)	spatial variations between the different estimates

Vulnerability	1) Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of environmental damages. Vulnerability is a function of the character, magnitude, and rate of environmental damage and variation to which a system is exposed, its sensitivity, and its adaptive capacity (adapted from http://climate-adapt.eea.europa.eu/glossary#linkVulnerability, data accessed 18/03/2016) 2) The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (IPCC WGII AR5 Glossary) 3) Vulnerability is a broad term encompassing concepts such as rarity, resilience and recoverability of e.g. species or ecosystems
Weighting, Binary	Impacts are assigned either no weight or equal importance, based on criteria decided by the practitioner.
Weighting, Distance to target	Impacts are weighted according to their proximity to a target. It includes the normative target approach, where the targets are defined based on regulations (e.g. the CO_2 reduction target).
Weighting, Monetary	Impacts are weighted according to their estimated economic value.
Weighting, Panel	Impacts are weighted based on the opinions of a group of people, and their preferences are translated directly into numeric values or ranges.

Glossary References

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Peer Review report

Prepared by Mary Ann Curran, TRC Chair, October 12, 2016

Throughout 2014 and 2015, the various working groups of the UNEP/SETAC Life Cycle Initiative have been developing the Phase 3 work, making substantial progress in the main flagship activities. As deliverables are produced, it is essential that a process be followed to ensure that they are in-line with the mission of the Initiative and original objectives of the flagship work areas, while meeting quality standards. This is achieved by following a deliberate review process conducted by the standing Technical Review Committee (TRC).

Following is the quality report prepared by Mary Ann Curran (BAMAC Ltd. and Editor-in-Chief of the *International Journal of Life Cycle Assessment)*, TRC Chair, for the effort entitled "Coordination and delivery of technical review: Pellston Workshop Report, Environmental LCIA Indicators." The present quality report evaluates and summarizes both the review process and the peer review results.

Background

Preparation of the LCIA indicators report and the Pellston process occurred in roughly four phases along the following timeline:

- The preparatory phase, September 2015 through December 2015;
- The workshop itself, January 24-29, 2016, in Valencia, Spain;
- The preliminary report review phase, from to July 8, 2016 to September 2016.
- Review of revised report and responses to comments, October 2016.

In the first phase, the purpose and set-up of the workshop was defined and discussed, and the list of invited contributors was made. The Chair of the TRC was informed of the overall progress of this activity but not directly involved in meetings or discussions. Nor does the Chair possess a complete archive of everything that was discussed. Nevertheless, the TRC Chair has been able to get a general idea of this phase. The discussion on purpose, set-up and participant list was well-organized. Many meetings of the workshop organizers and the UNEP/SETAC Life Cycle Initiative Board have devoted time to find a good balance between the interests of business, industry, academia and other stakeholders. The list of participants reflected a balance of perspectives in terms of affiliation, geography and gender. Since the TRC Chair was not directly involved in the preparatory phase of the workshop, and did not participate in the workshop or in the writing of the workshop report, the review focused on the final workshop report.

Technical Review Committee (TRC) Review

The TRC is responsible for assessing the development and review process that was followed, including ensuring that 1. The review is objective, 2. Critical issues are identified and addressed, and 3. The review process was of a technical nature, as well as editorial. Furthermore, the TRC is responsible for checking the activity against the original project proposal and ensuring an adequate balance of geographic representation and gender, as well as field of expertise, was incorporated in the review. The TRC Chair consolidates a statement and recommendations to the Life Cycle Initiative's Board (the ILCB) on the deliverables reviewed.

On July 8, 2016, Dr. Mary Ann Curran, BAMAC Ltd., serving as the Technical Review Committee (TRC) chair for the UNEP/SETAC Life Cycle Initiative, was asked to supervise the review of the outcome of the task "Coordination and delivery of technical review Pellston Workshop Report, Environmental LCIA Indicators." Because the Pellston Workshop® process[1] results in a final report reflecting the mutual understanding and general consensus achieved between the participants

1 The Pellston process refers to SETAC's use of a concentrated workshop to produce a monograph; see http://www.setac.org/node/104. The first workshop of this type was held in Pellston, Michigan, in 1977.

during the meeting, substantial changes to the report are impossible to adopt after the workshop has closed.

The review process consisted of a classical peer review approach in which the draft document (i.e. the draft workshop report) was sent to qualified reviewers who had agreed to supply comments. These reviewers did not participate in the workshop. All gratefully agreed to provide feedback on specific chapters within a very short deadline. In addition, the SETAC representative, Bruce Vigon, who did participate in the workshop, commented on the entire document. The list of reviewers includes the following individuals:

Markus Berger (Technical University Berlin); Debbie Bennett (University of California Davis); Kate Brauman (University of Minnesota); Jorge Soto, Luis Ortega, and Yuki Kabe (Braskem); David Cockburn (TetraPak); Petra Döll (Goethe University); Mark Goedkoop (Pré Consultants); Gert van Hoof (P&G); Henry King (Unilever); Jon Levy (Boston University); Sarah McLaren (Massey University); Andy Reisinger (New Zealand Agricultural Greenhouse Gas Research Center).

Peer Review of the Draft Document

The TRC received the complete set of draft chapters, including an executive summary, from the workshop organizers, Rolf Frischknecht and Olivier Jolliet. These chapters were first given a cursory review by the TRC Chair to determine completeness. The chapters were then distributed to the individuals who agreed to serve as peer reviewers. Most chapters were reviewed by two individuals; this was the minimum number of reviews deemed appropriate and necessary by the TRC Chair. The only exception was the chapter on land use which was reviewed by four people. The reviewers were given three weeks to submit comments.

Each reviewer was reminded that the aim of a Pellston Workshop® is to capture the discussion that occurred during the week-long gathering. So while major rewrites are not an option in the review process, the intent is to verify the accuracy of the science and proposals being put forth. Also, they were told by the TRC Chair that the report would undergo a thorough editorial review after the technical review, so comments to that effect were not necessary.

Reviewers were instructed to submit comments either marked directly on the file or listed in a Word document. All chose to submit marked up pdf files, including a few general comments in email messages to the TRC Chair. The Chair compiled the individual comments into a single file for each chapter and forwarded them to the workshop organizers.

TRC Chair Recommendation

Overall, the peer review comments were positive and supportive of the effort to move toward global guidance for the selected impact categories. However, some reviewers found it a bit premature for UNEP/SETAC to position and endorse many of the indicators and concepts from the workshop as global guidance. Many of the indicators, as well as the revised framework, are unproven/lack validation both scientifically and from a practical implementation perspective (i.e. working with available inventories and information). Both need rigorous testing by engaging expertise domains such as health professionals, toxicologists, etc., in order to be shown to be practical. Practical application was an important aspect for reviewers.

Many comments were editorial in nature or aimed to help improve the clarity of the text. These comments were delivered to the workshop organizers to help develop the final version of the report. Other comments were found to be more substantive in character. The Life Cycle Initiative is strongly encouraged to make the complete set of comments and responses to the individual comments publicly available on their website, or some other readily accessible site.

Review statement

As a whole, the TRC acknowledges that the Pellston Workshop® process was followed closely and resulted in a successful meeting and a valuable document on an important topic. People from different backgrounds and affiliations collaborated in a fruitful way to deliver this latest discussion on global guidance for LCIA. The TRC fully expects the present guidance document will help advance the world-wide understanding and application of life cycle models for the selected impact categories.

Note from the editors:

All peer review comments were assessed and incorporated when deemed appropriate and relevant. The complete set of comments submitted by the peer reviewers are available upon request from info@ lifecycleinitiative.org.

List of Public Stakeholder Consultation Events

International Symposium on Life Cycle Impact Assessment - Towards development of global scale LCIA method – Yokohama, Japan – 23 November 2012

Open stakeholder consultation "Global guidance on environmental life cycle impact assessment indicators", 16-17 May, Glasgow, United Kingdom, 2013

Open stakeholder consultation "Global guidance on environmental life cycle impact assessment indicators", Basel, Switzerland 15 May, 2014

Open stakeholder consultation, "Global guidance on environmental life cycle impact assessment indicators", Barcelona, Catalonia, Spain, 7 May 2015

Special session of the SETAC-Nantes meeting "Consensus building in life cycle impact assessment", 25 May 2016, Nantes, France, 2016

Life Cycle Impact Assessment Worskshop, V Brazilian Life Cycle Management Congress, Fortaleza, Brazil, 19th September 2016

Special session of the V Brazilian Life Cycle Management Congress on "UNEP/SETAC Consensus Methods for LCIA", Fortaleza, Brazil, 21st September 2016

Special session of the LCA XVI conference "The UNEP SETAC Life Cycle Initiative flagship project on Global guidance on environmental life cycle impact assessment indicators", Charleston, SC, USA, 27 September 2016

Special session of the Eco-balance conference "The UNEP SETAC Life Cycle Initiative flagship project on Global guidance on environmental life cycle impact assessment indicators", Kyoto, Japan, 6 October 2016

About the Life Cycle Initiative

The Global Life Cycle Initiative was established by UNEP and SETAC. Among other things, the Life Cycle Initiative builds upon and provides support to the on-going work of UNEP on sustainable consumption and production, such as industry outreach, industrial pollution management, sustainable consumption, cleaner and safer production, Global Reporting Initiative (GRI), Global Compact, UN Consumer Guidelines, tourism, advertising, eco-design, and product service systems.

The Initiative's efforts are complemented by SETAC's international infrastructure and its publishing efforts in support of the LCA community.

The Life Cycle Initiative is a response to the call from governments for a life cycle economy in the Malmö Declaration (2000). It contributes to the 10-year framework of programmes to promote sustainable consumption and production patterns, as requested at the World Summit on Sustainable Development (WSSD) in Johannesburg (2002).

The Life Cycle Initiative's vision is a world where life cycle approaches are mainstreamed and its mission is to enable the global use of credible life cycle knowledge for more sustainable societies.

Our current work is building on the Life Cycle Initiative's continual strength to maintain and enhance life cycle assessment and management methodologies and build capacity globally. As we look to the future, life cycle assessment (LCA) and life cycle management (LCM) knowledge is the Life Cycle Initiative's anchor, but we will advance activities on LCA and LCM to make a difference within the real world.

Therefore, the renewed objectives are the following:

Objective 1: Enhance the global consensus and relevance of existing and emerging life cycle methodologies and data management

Objective 2: Expand capability worldwide to apply and to improve life cycle approaches; making them operational for organizations

Objective 3: Communicate current life cycle knowledge and be the global voice of the life cycle community to influence and partner with stakeholders

For more information,
www.lifecycleinitiative.org

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About SETAC

The Society of Environmental Toxicology and Chemistry (SETAC) is a professional society in the form of a not-for-profit association, established to promote the use of a multidisciplinary approach to solving problems of the impact of chemicals and technology on the environment. Environmental problems often require a combination of expertise from chemistry, toxicology, and a range of other disciplines to develop effective solutions. SETAC provides a neutral meeting ground for scientists working in universities, governments, and industry who meet, as private persons not bound to defend positions, but simply to use the best science available.

Among other things, SETAC has taken a leading role in the development of life cycle management (LCM) and life cycle assessment (LCA).

The organization is often quoted as a reference on LCA matters.

For more information,

www.setac.org

About the UNEP Division of Technology, Industry and Economics (DTIE)

Set up in 1975, three years after UNEP, the Division of Technology, Industry and Economics (DTIE) provides solutions to decision makers and helps change the business environment by offering platforms for multi-stakeholder dialogue and cooperation, innovative policy options, pilot projects, and creative market mechanisms to improve the quality of the environment and the well-being of citizens.

Within UNEP, DTIE has the mandate of delivering on environmental sustainability through technology, industry, and economic policy by addressing environmental issues at global and regional levels, providing leadership and encouraging partnerships, and by informing and enabling nations and people to improve their quality of life without compromising that of future generations.

DTIE plays a leading role in three of UNEP's seven strategic priorities, namely in climate change, chemicals and waste, and resource efficiency.

The Office of the Director, located in Paris, coordinates activities through:

- The **Chemicals and Waste Branch** (Geneva, Paris and Osaka), which catalyzes global actions to bring about the sound management of chemicals, the improvement of chemical safety and the management of waste.
- **The International Environmental Technology Centre - IETC** (Osaka) promotes the collection and dissemination of knowledge on environmentally sound technologies with a focus on waste management. The broad objective is to enhance the understanding of converting waste into a resource and thus reduce impacts on human health and the environment (land, water, and air).
- **OzonAction** (Paris) supports the phase-out of ozone depleting substances in developing countries and countries with economies in transition to ensure implementation of the Montreal Protocol.
- The **Economy and Trade Branch** (Geneva), which helps countries to integrate environmental considerations into economic and trade policies, and works with the finance sector to incorporate sustainable development policies. This branch is also charged with producing green economy reports.
- The **Energy, Climate, and Technology Branch** (Paris, Nairobi, and Copenhagen), which fosters energy and transport policies for sustainable development and encourages investment in renewable energy and energy efficiency.
- The **Sustainable Lifestyles, Cities and Industry Branch** (Paris), which delivers support to the shift to sustainable consumption and production patterns as a core contribution to sustainable development.

DTIE works with many partners (other UN agencies and programmes, international organizations, governments, non-governmental organizations, business, industry, the media, and the public) to raise awareness, improve the transfer of knowledge and information, foster technological cooperation, and implement international conventions and agreements.

For more information,

www.unep.org/dtie

Which quantitative and life cycle-based indicators are best suited to quantify and monitor man-made impacts on climate change, biodiversity, water resources, and other aspects of the biophysical environment?

The Global Guidance for Life Cycle Impact Assessment Indicators (Volume 1) goes a long way to address this question by identifying the "current best available practice" in a variety of areas: climate change, human health impacts of fine particulate matter, water use impacts, and land-use impacts on biodiversity. The global importance of these impact areas is also recognized in specific Sustainable Development Goals (SDGs).

This guidance document contains a reservoir of useful and practical information that reflects the dedicated effort and collaboration of many scientists, engineers, and life cycle assessment (LCA) practitioners from around the globe. Aimed at LCA practitioners and method developers, it enhances the comprehensive and consistent assessment of impacts in production and consumption systems throughout their life cycle, making explicit any potential trade-offs and supporting more sustainable processes. It provides a significant leap forward in the environmental representation and accuracy of internationally endorsed, scientifically robust, and stable indicators while enhancing comparability among LCA studies.

This guidance document should be on the physical and electronic desktops of practitioners as well as those that will benefit from and make use of the outputs of LCA.

www.unep.org

United Nations Environment Programme
P.O. Box 30552 - 00100 Nairobi, Kenya
Tel.: +254 20 762 1234
Fax: +254 20 762 3927
e-mail: uneppub@unep.org

UNEP

For more information, contact:
UNEP DTIE
Sustainable Lifestyles, Cities and Industry Branch
1 rue Miollis
Building VII
75015 Paris
France
Tel: +33 1 4437 1450
Fax: +33 1 4437 1474
E-mail: unep.tie@unep.org
www.unep.org/dtie

ISBN: 978-92-807-3630-4

DTI/2081/PA